Effect of Mechanical Stress on Gate Current and Degradation in AlGaN/GaN HEMTs

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Florida MURI Review
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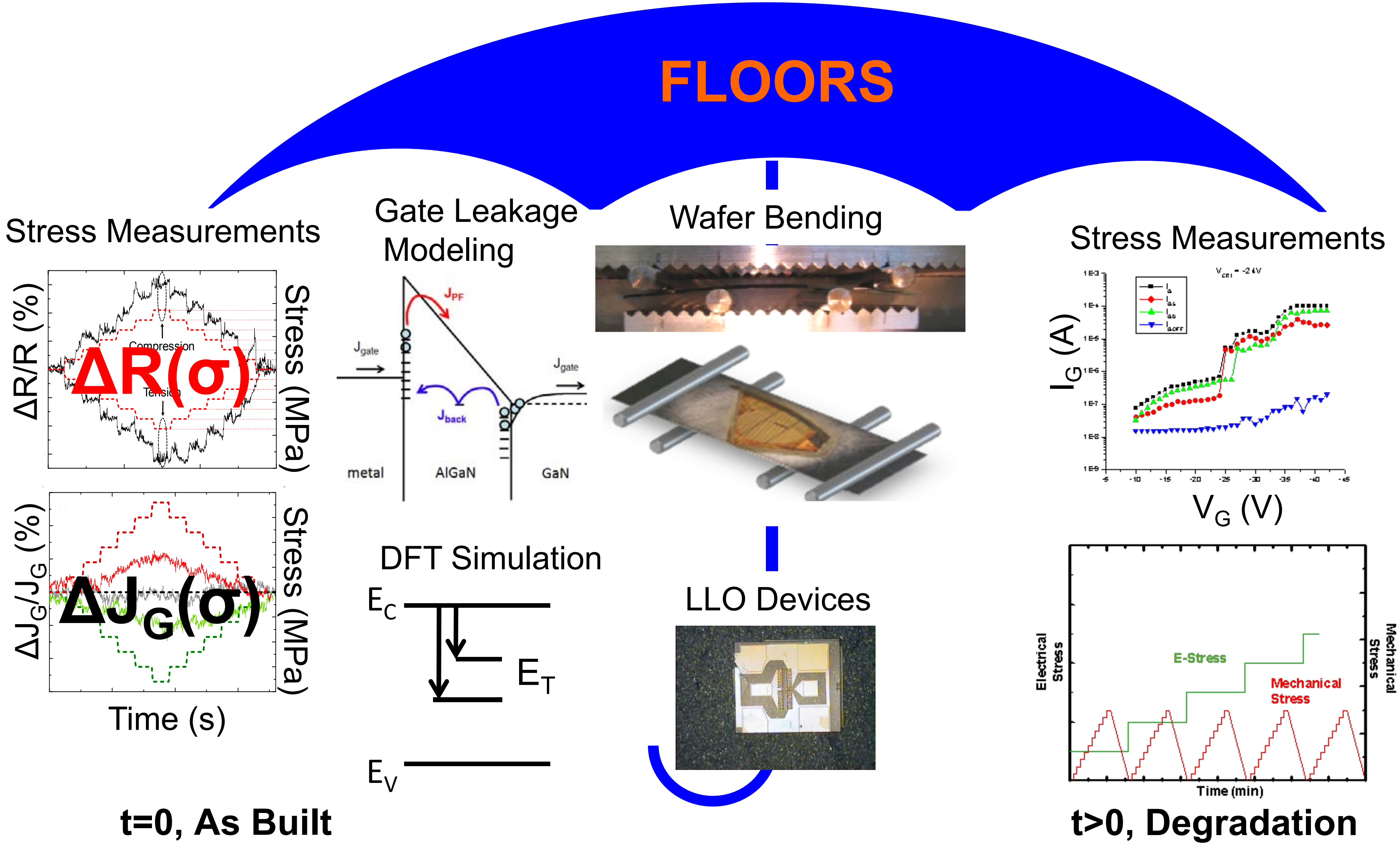
Outline

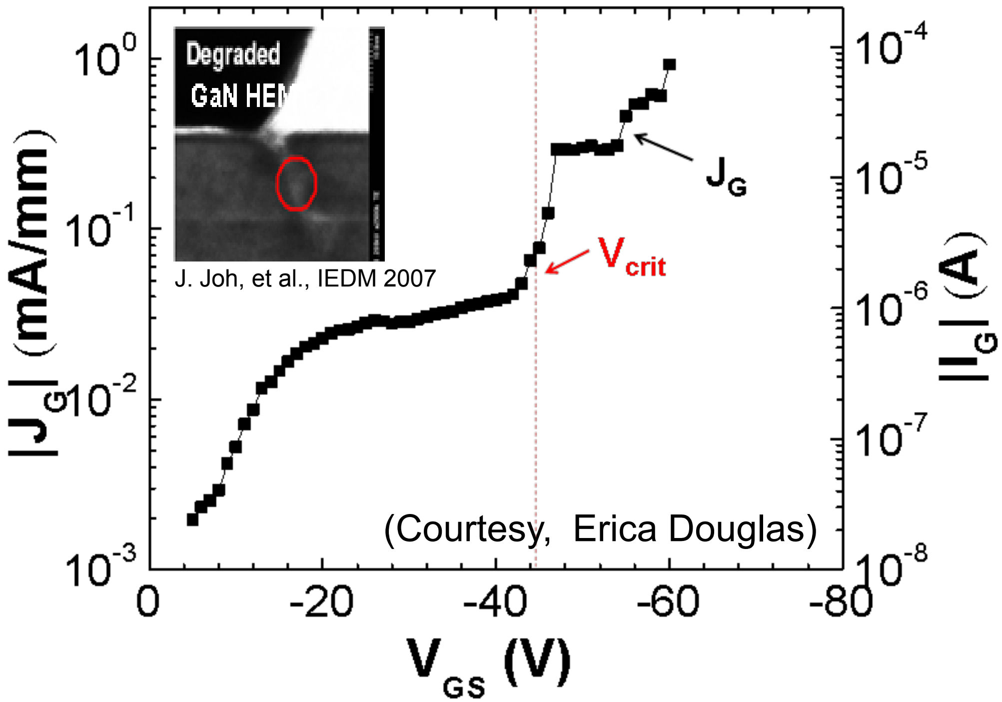
- Motivation
- Stress Dependence of Gate Current and Characterization of Electric Field in AlGaN Barrier
- Simulation of the Dominant Stress-Altered Gate Leakage Current
- Gate Current Degradation under Mechanical and Electrical Stress
- Summary

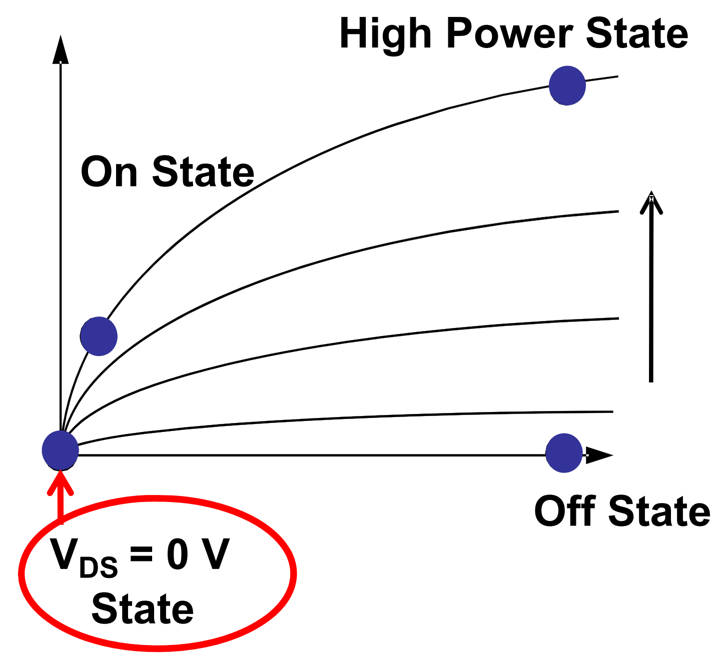
Mechanical Stress on GaN HEMT Reliability



Gate Current Degradation

Large E_{AlGaN} → Inverse PZ → **Mechanical Stress** → Defect formation → **Device Breakdown** → **Increase in J_G**





Systematically investigate impact of mechanical stress on J_G

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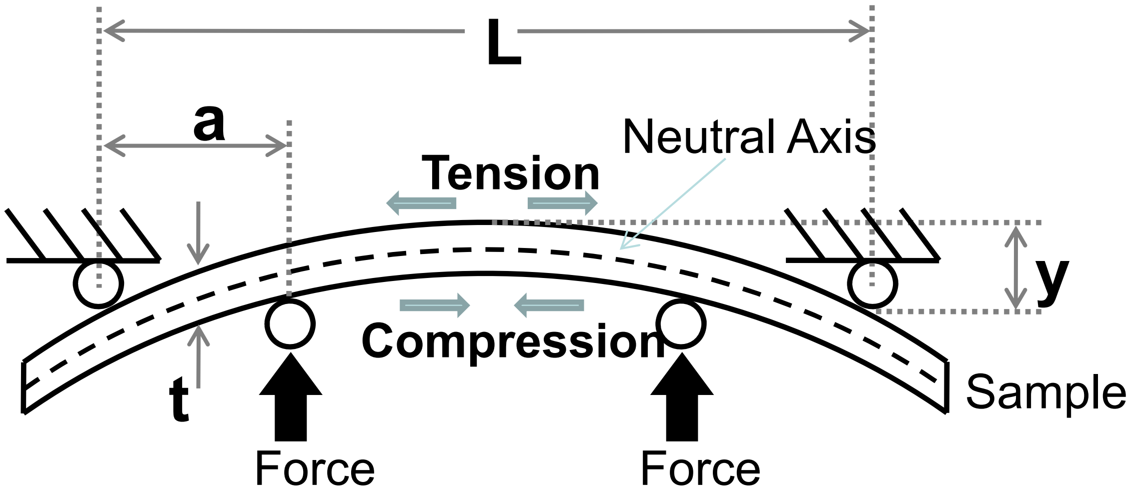
Wafer Bending (4-Point Bending)

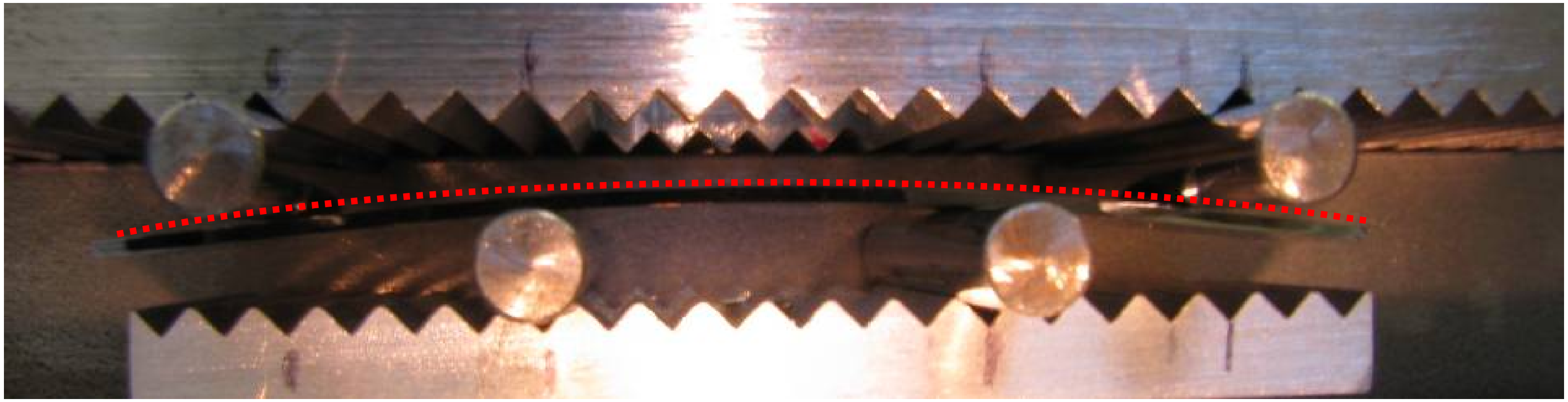
Stress on upper surface at the center of the substrate:

$$\sigma = \frac{E \cdot t \cdot y_{x=a}}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)}$$

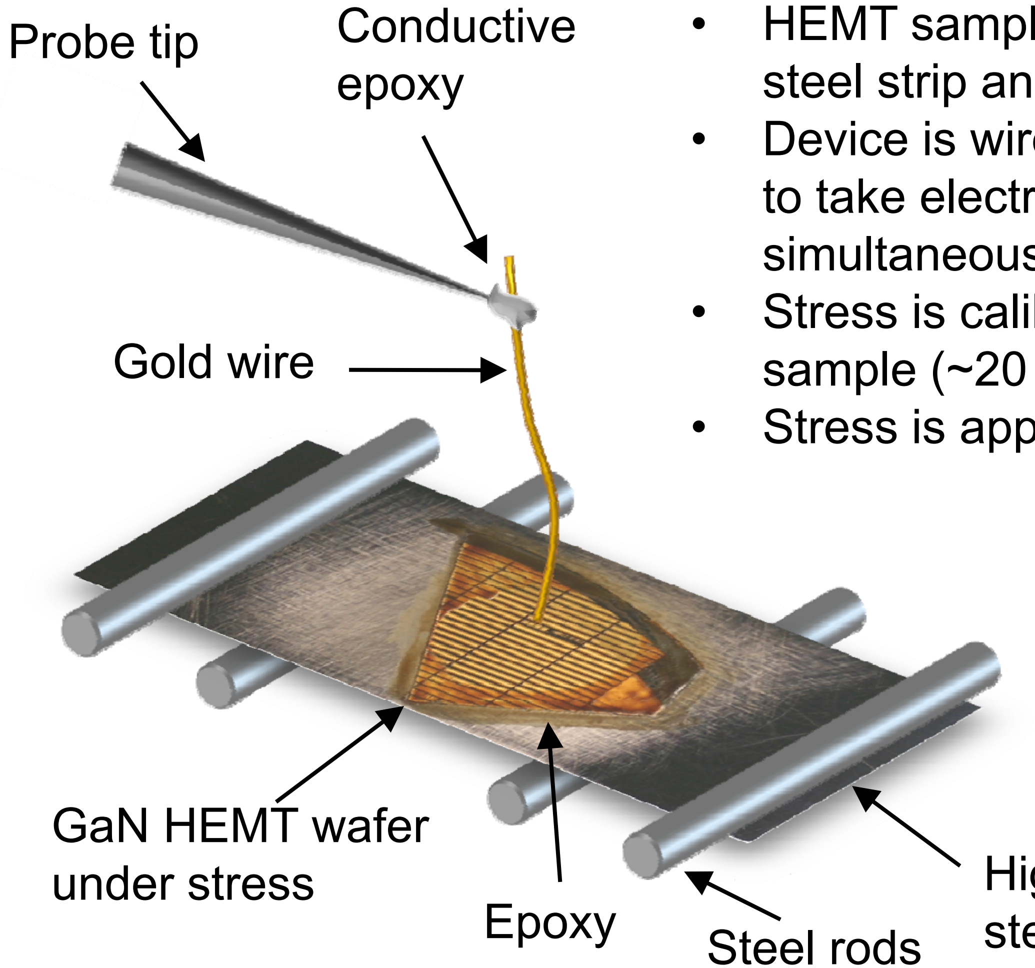
[*Strength of Materials, edited by S. Timoshenko Krieger, Melbourne, FL,*1976]

E = Young's modulus
t = sample thickness
y = vertical displacement
a, L = rod spacing





GaN HEMT Wafer Bending Setup



- GaN HEMT wafer samples are too small for 4-point bending
- HEMT sample attached to high carbon stainless steel strip and inserted into bending setup
- Device is wirebonded and connected to probe tips to take electrical measurements while simultaneously applying stress
- Stress is calibrated using strain gauge mounted on sample (~20 MPa/graduation)
- Stress is applied longitudinal to channel direction

J_G Stress Measurement Procedure

1. **Bias device in dark measuring J_G**

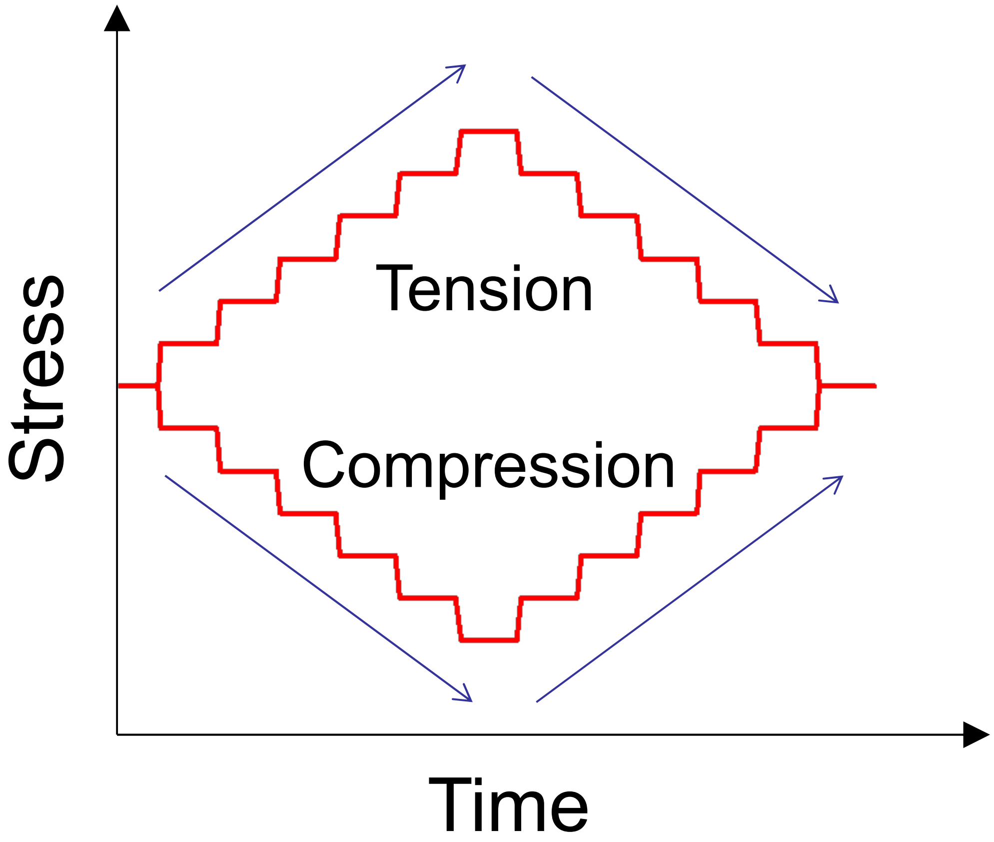
   V_G = -0.1 to – 4 V

2. **J_G stable**

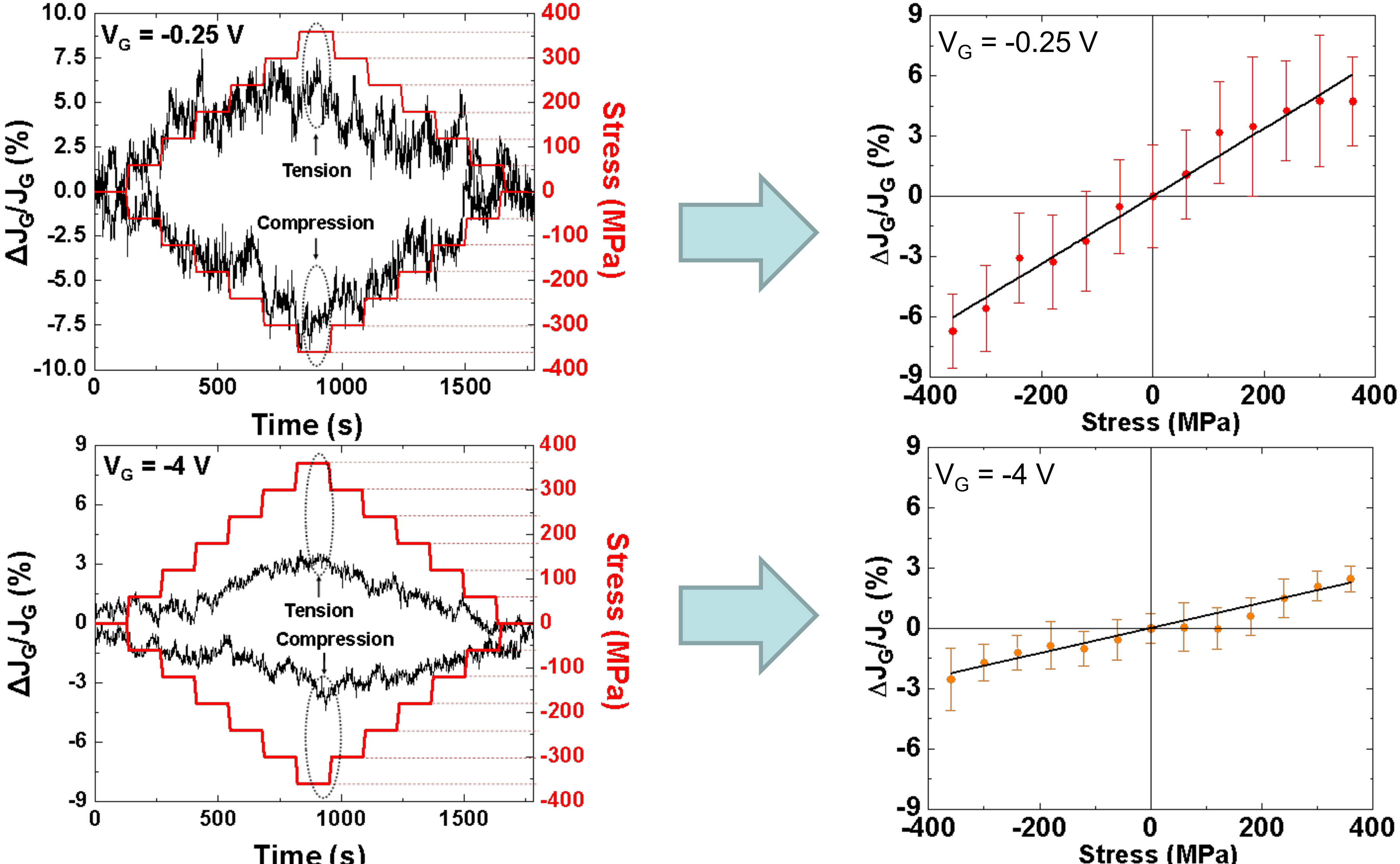
3. **Incrementally apply stress**

4. **Incrementally release stress**

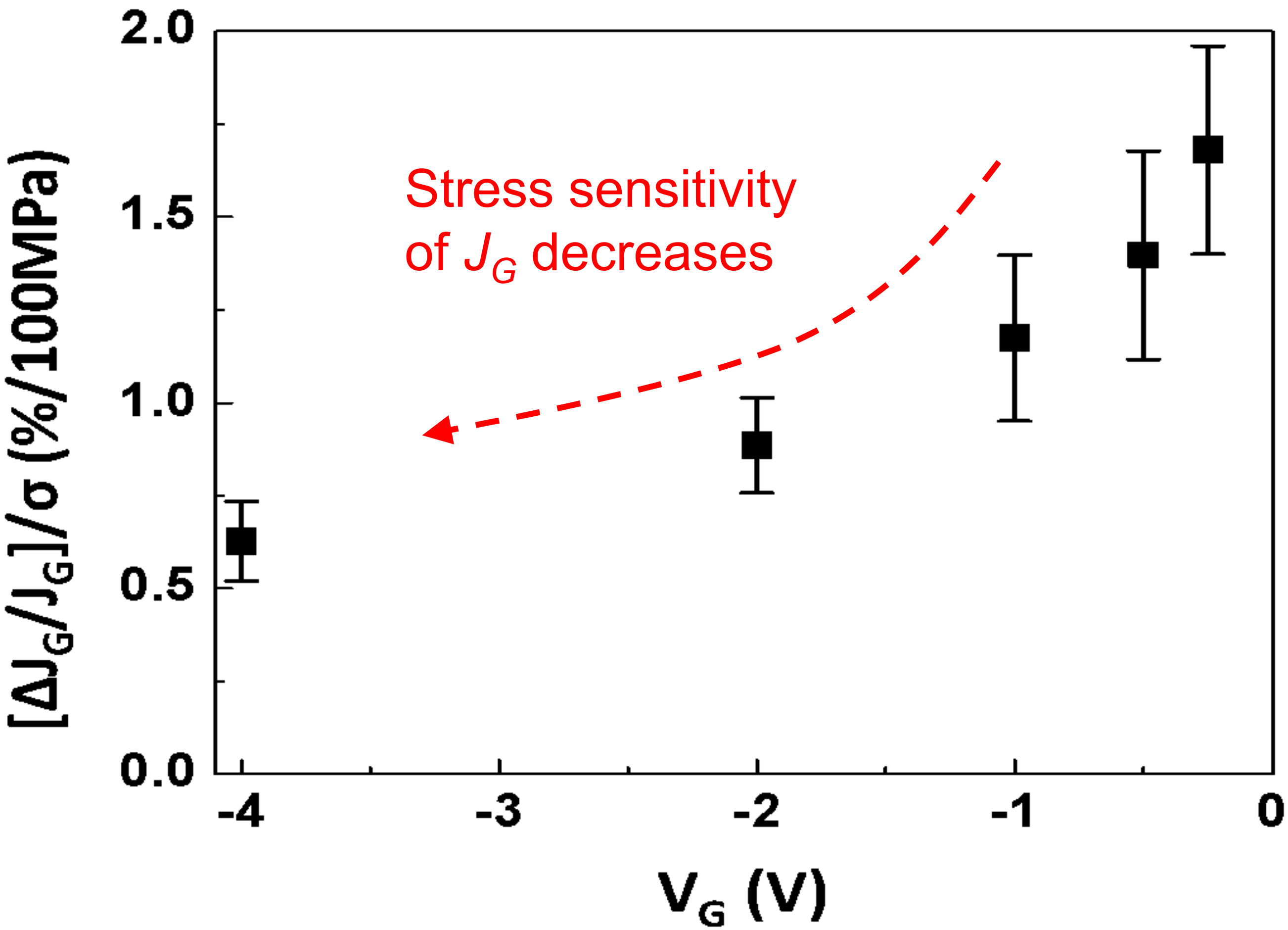
5. **Avg. J_G at each stress**



Experimental Results



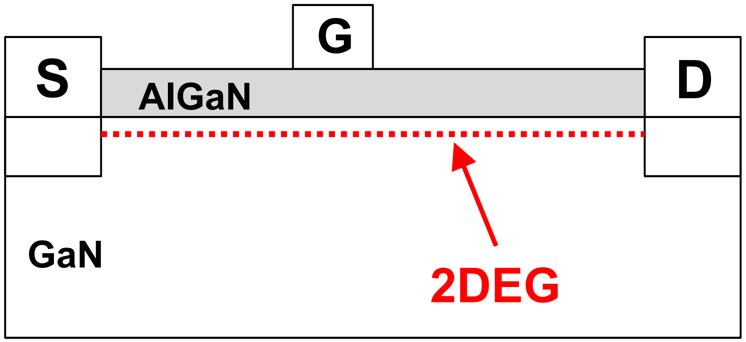
Bias and Stress Sensitivity of J_G

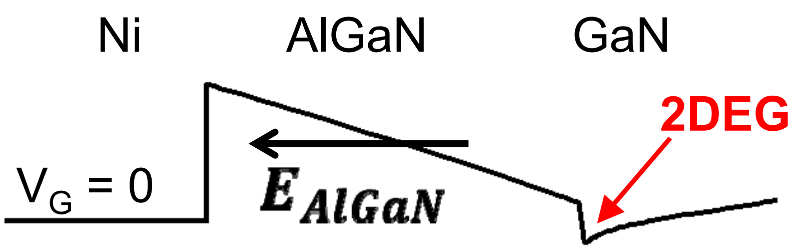


Characterize J_G mechanism and impact of stress on J_G

Device Operation

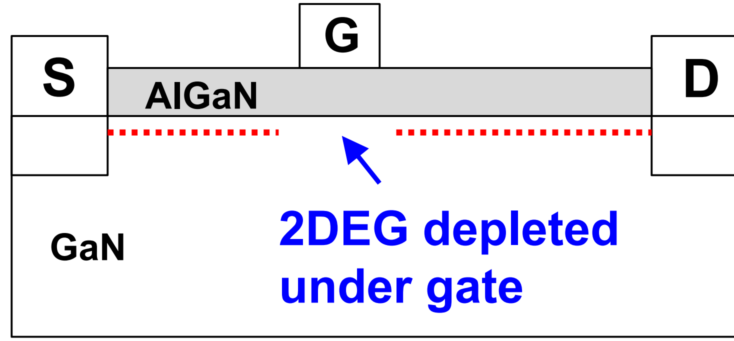
ON Condition

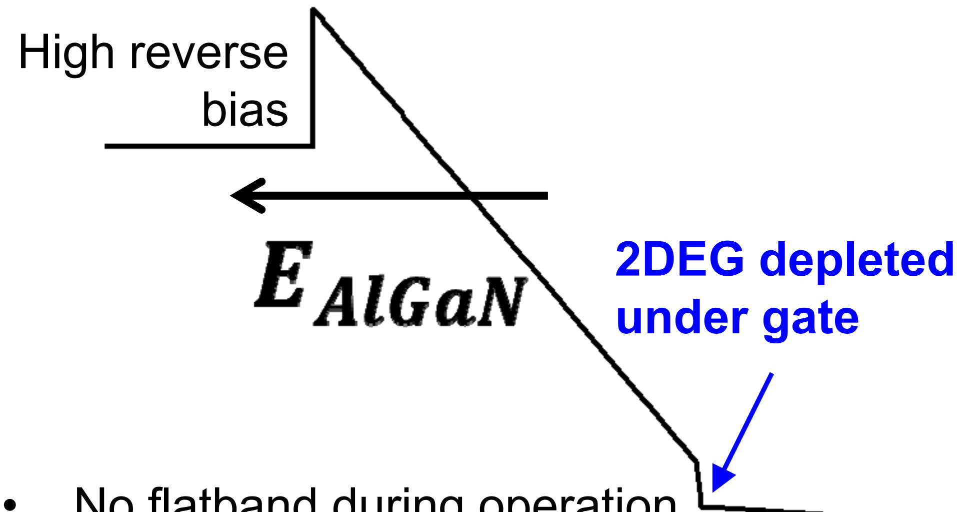




- Built-in field at $V_G = 0$
- 2DEG is not inversion electrons (from surface states)

OFF Condition

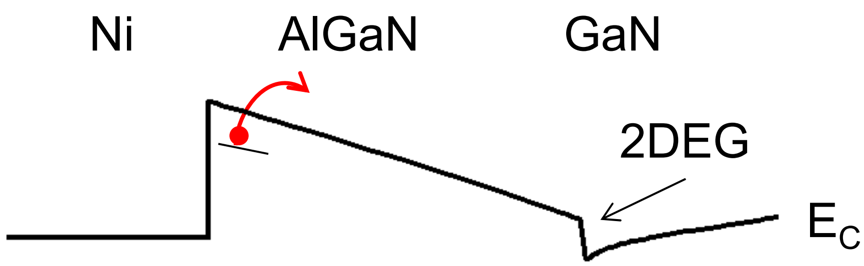




- No flatband during operation
- Device is turned off by depleting 2DEG
- V_T is defined when 2DEG is depleted

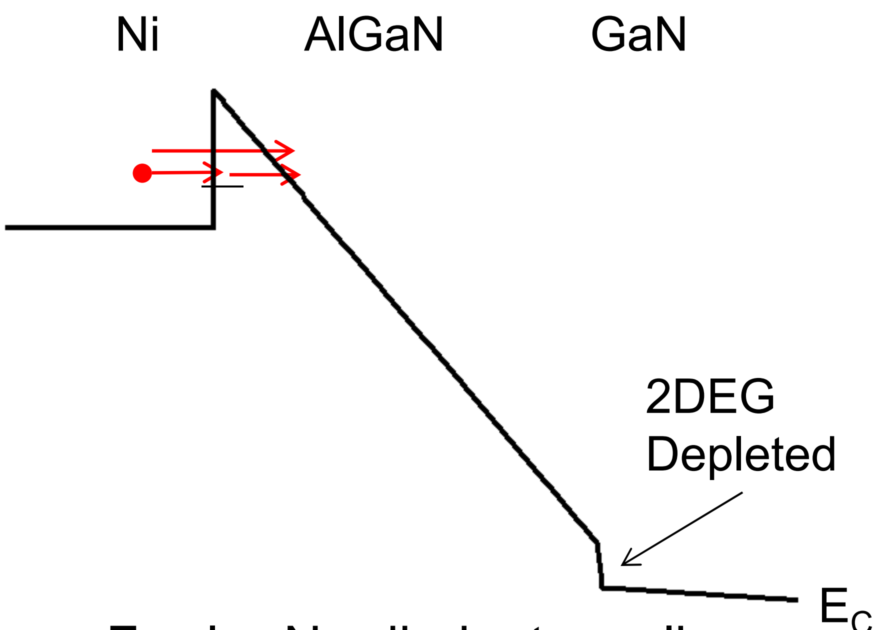
Gate Leakage Transport Mechanisms

ON Condition



- Poole-Frenkel emission

OFF Condition



- Fowler-Nordheim tunneling
- Trap-assisted-tunneling
- Phonon-assisted tunneling

To characterize gate leakage, need E_{AlGaN}

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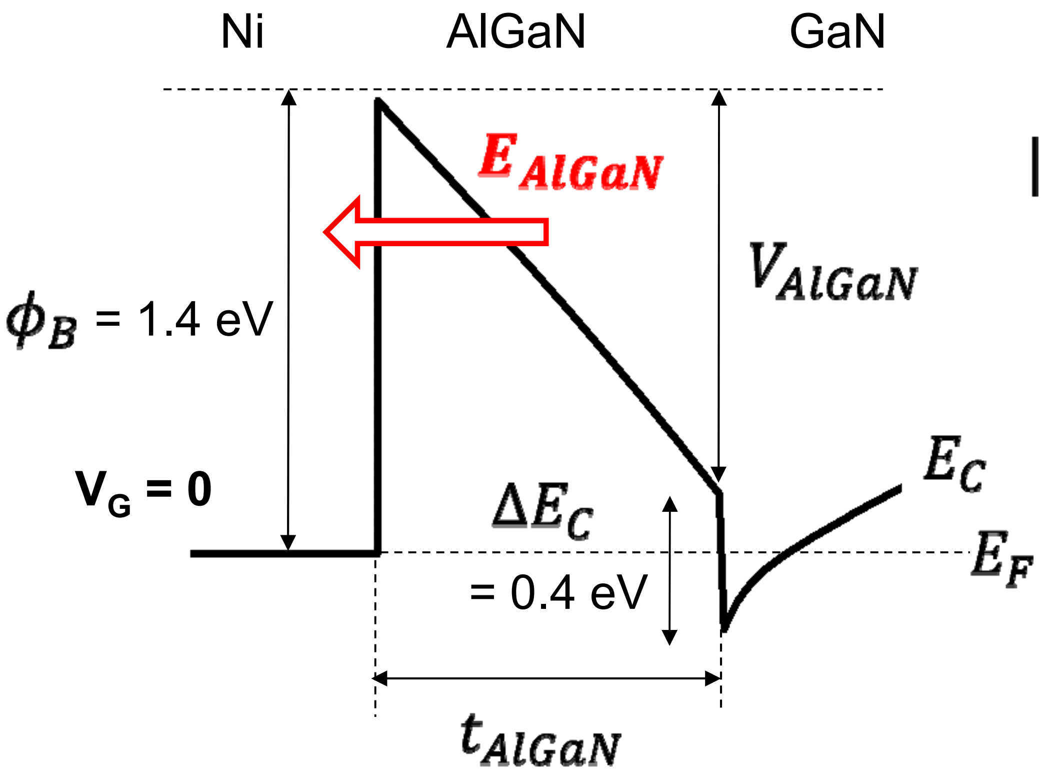
The Foundation for The Gator Nation

GATOR Engineering UNIVERSITY OF FLORIDA

1D E_{AlGaN} Calculation



$$|E_{AlGaN}| = \frac{V_{AlGaN}}{t_{AlGaN}} = \frac{V_G - \psi_s}{t_{AlGaN}}$$

- E_{AlGaN} is a function of ψ_s
- 2DEG density (n_s) is used to calculate E_{AlGaN}

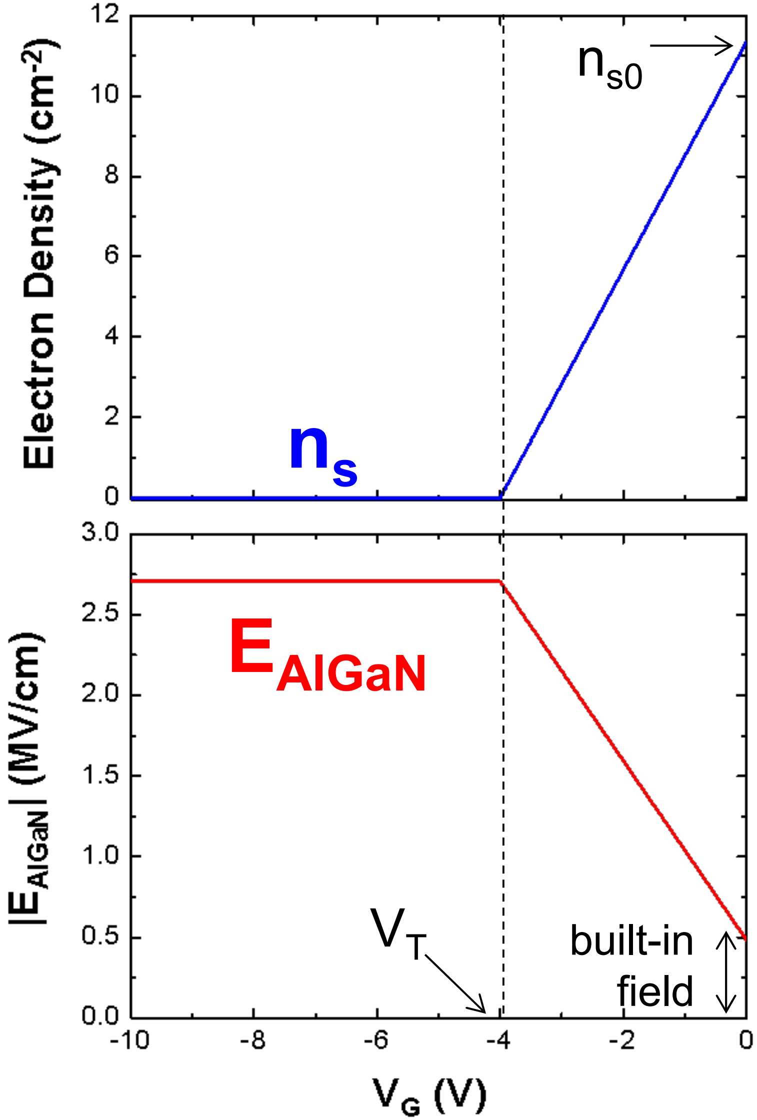
E_{AlGaN} depends on σ_{int} and n_s

- σ_{int} is constant
- n_s depends on gate voltage

"Gauss's Law"

$$|E_{AlGaN}| = \frac{\sigma_{int} - qn_s}{\epsilon_0 \epsilon_r}$$

Ideal Device: n_s and E_{AlGaN}



No trapped charge in ideal device

$$n_s = n_{s0} + \left(\frac{C_{AlGaN}}{q}\right) V_G$$

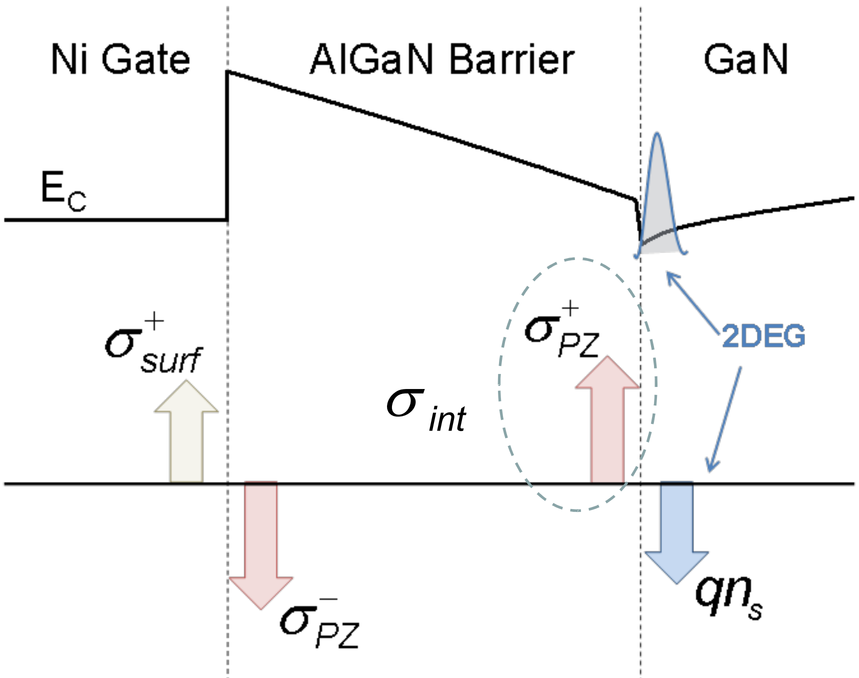
- no accumulation of holes ($n_i \sim 10^{-10}$ cm^{-3})

$$|E_{AlGaN}| = \frac{\sigma_{int} - q n_s}{\epsilon_0 \epsilon_r}$$

E_{AlGaN} saturates below V_T

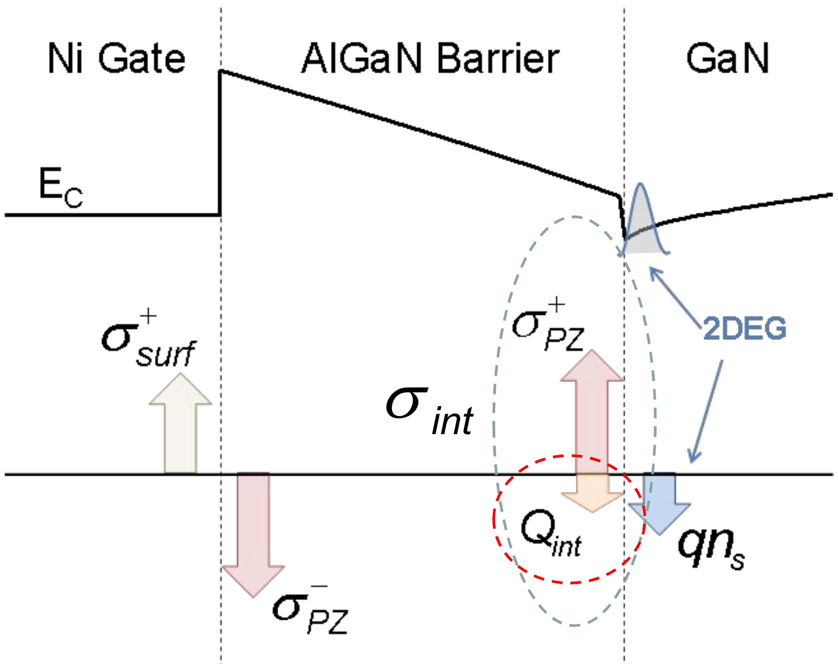
Ideal vs. Actual Device

Ideal device



- No charge traps ($\sigma_{int} = \sigma_{PZ}$)

Actual Device

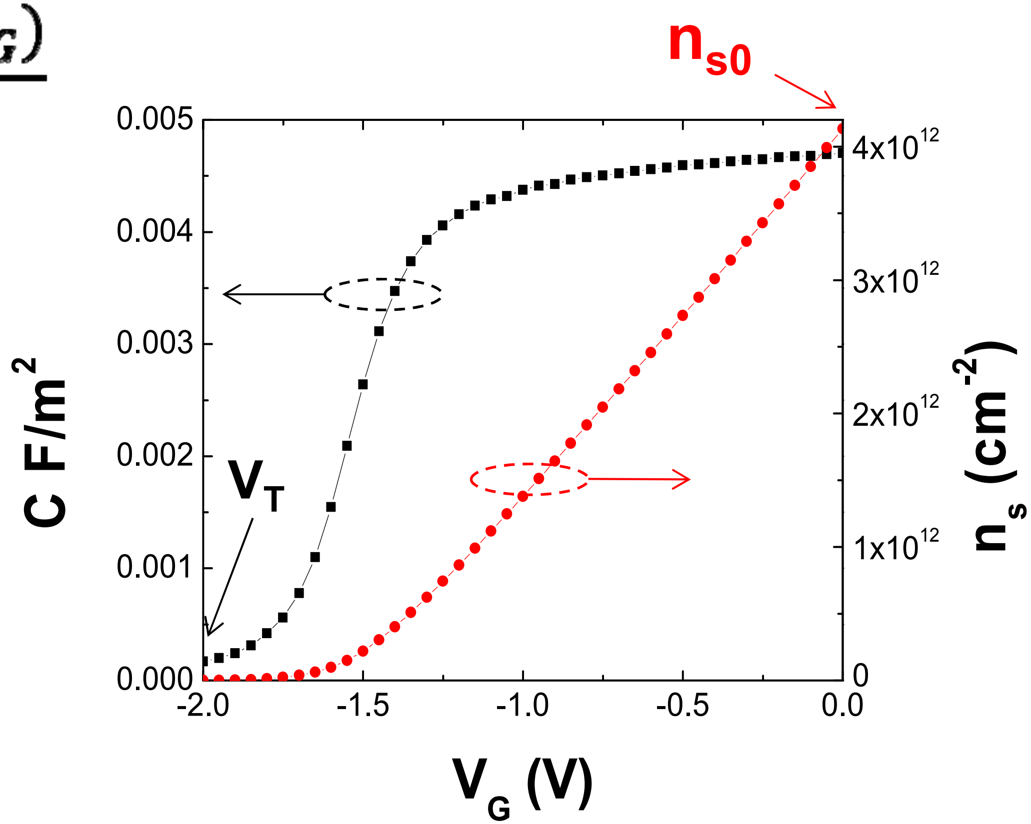


- Trapped charge reduces σ_{int} ($\sigma_{int} = \sigma_{PZ} – Q_{int}$)
- Lower n_s → lower V_T

Can experimentally calculate E_{AlGaN}

Calculating E_{AlGaN} of Actual Device

$$|E_{AlGaN}(V_G)| = \frac{\sigma_{int} - qn_s(V_G)}{\epsilon_0 \epsilon_r}$$



$n_s(V_G)$:

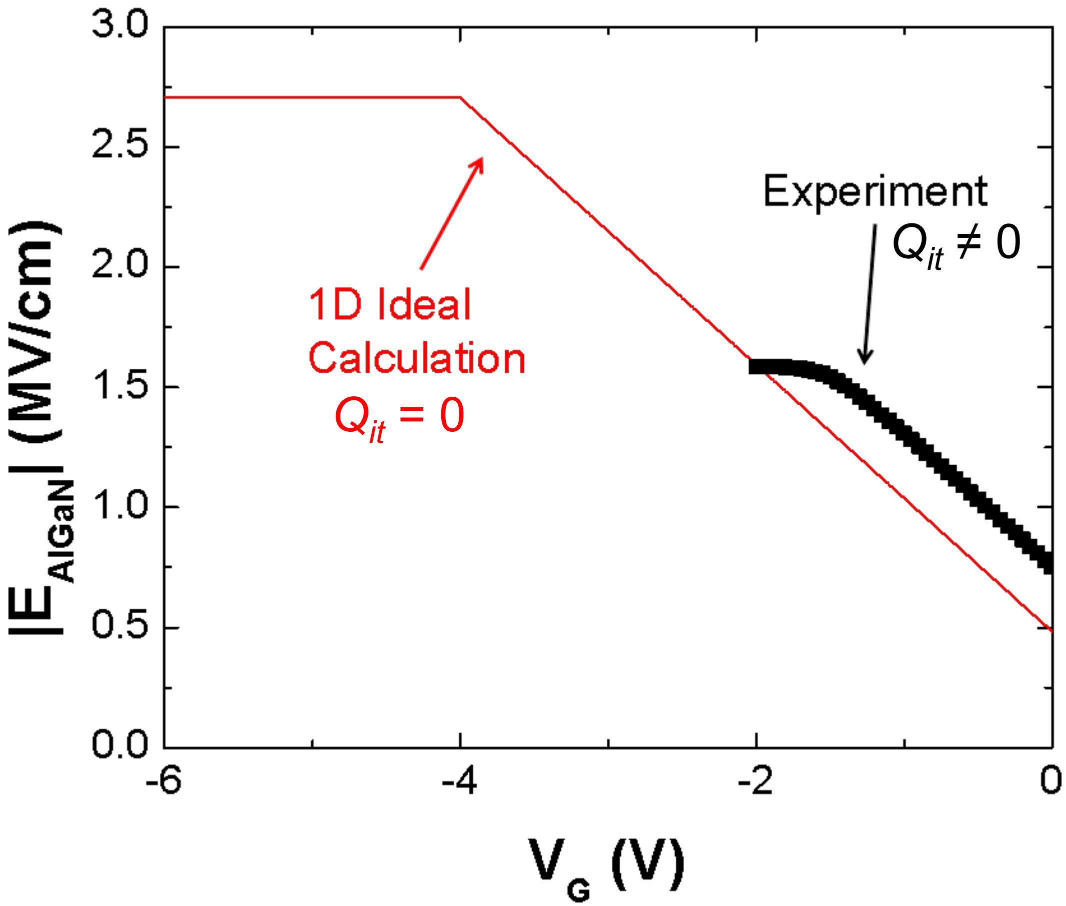
- Integration of the C–V curve

σ_{int}

- Calculate n_{s0}
- Take the difference of n_{s0} and charge induced by gate bias

Can determine experimentally the necessary parameters for 1D E_{AlGaN}

1D E_{AlGaN} of Actual Device



Q_{it} reduces σ_{int}

- Lowers V_T and E_{SAT}
- Increases $E_{AlGaN}(0)$

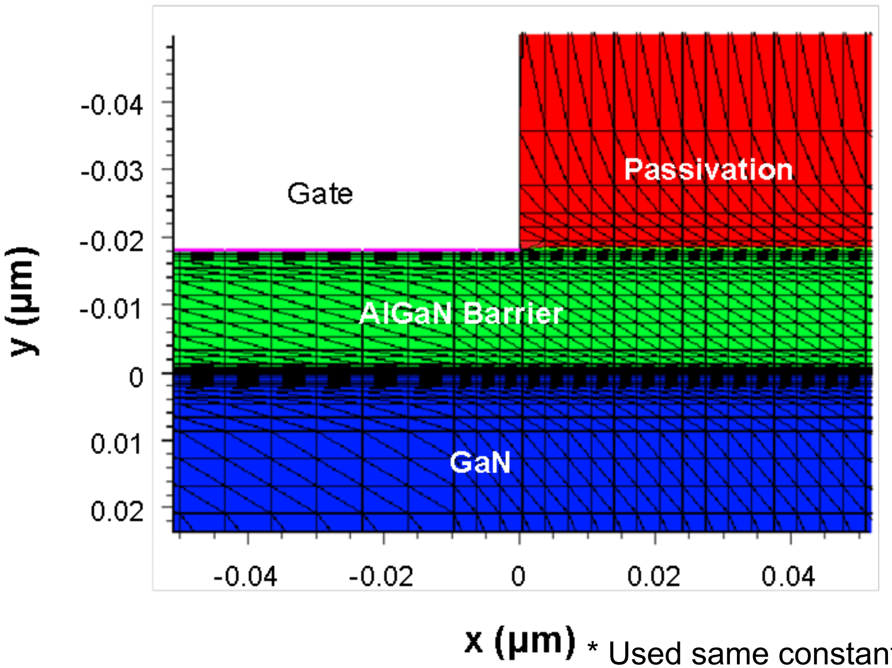
Can experimentally calculate E_{AlGaN} (matches 1D model)

Physics of E_{AlGaN} Saturation

1D model predicts saturation of E_{AlGaN}

$$|E_{AlGaN}| = \frac{V_G - \psi_s}{t_{AlGaN}}$$

Verify using Sentaurus 2D simulations



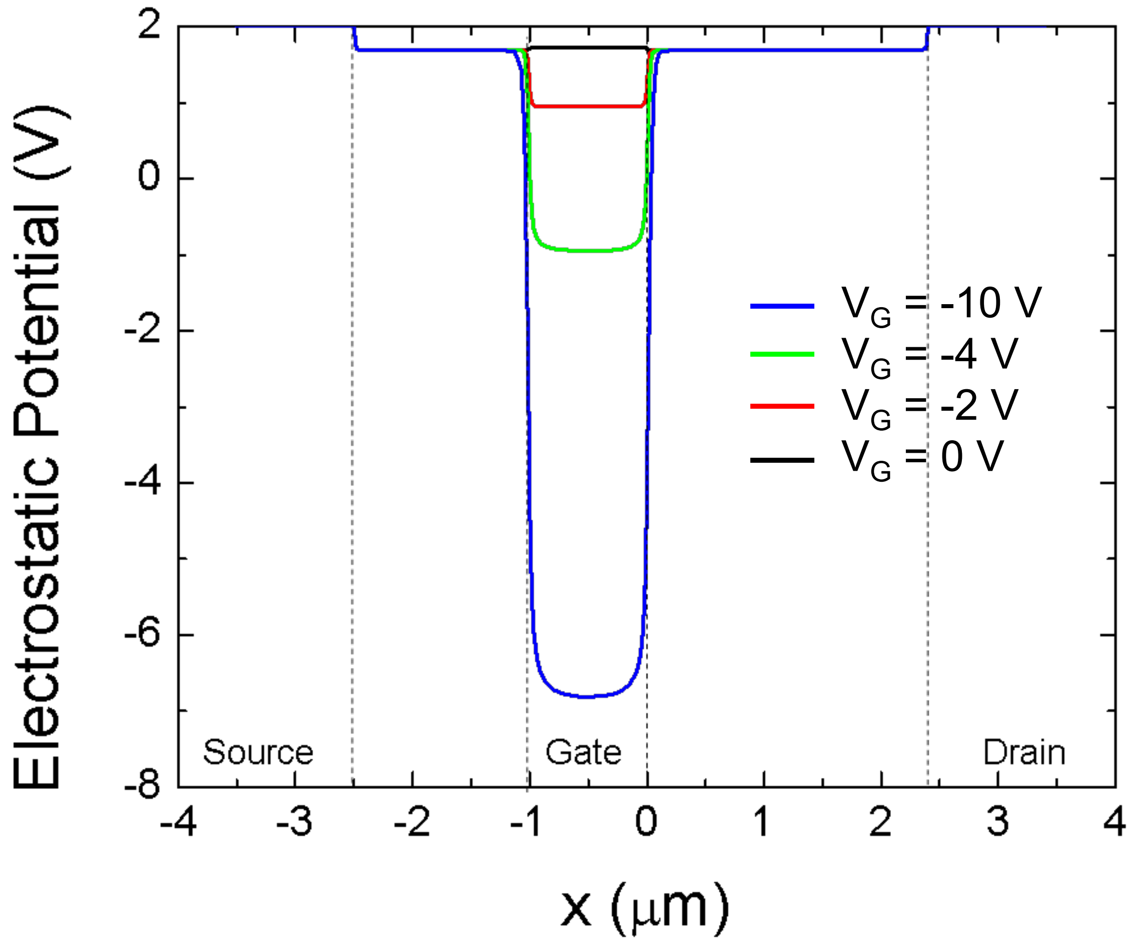
* Used same constants as 1D calculation

Self-consistently solve:

- Poisson's equation
- Electron/hole continuity equations

Piezoelectricity: Piezoelectric/spontaneous polarization implemented using fixed interface charge

Surface Potential in GaN

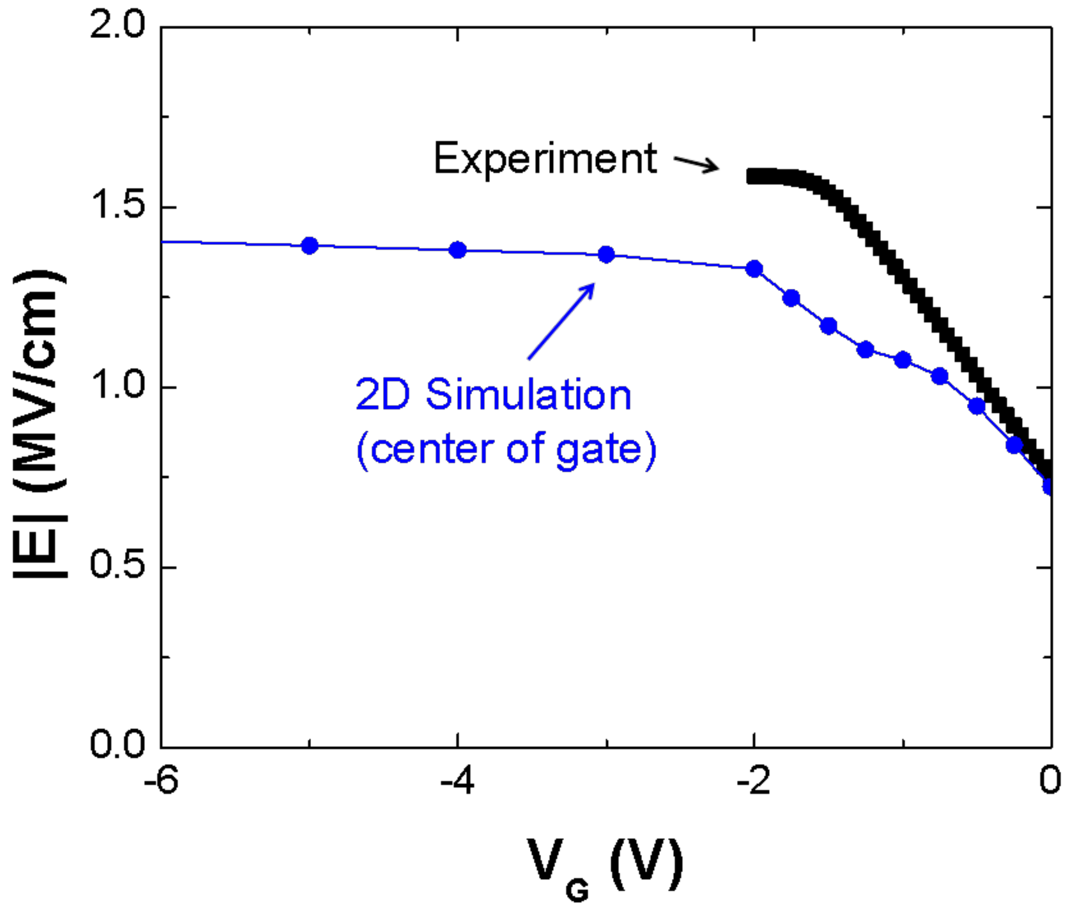


Potential extracted 0.5 nm below AlGaN/GaN interface

$$E_{AlGaN} = \frac{V_G - \psi_s}{t_{AlGaN}}$$

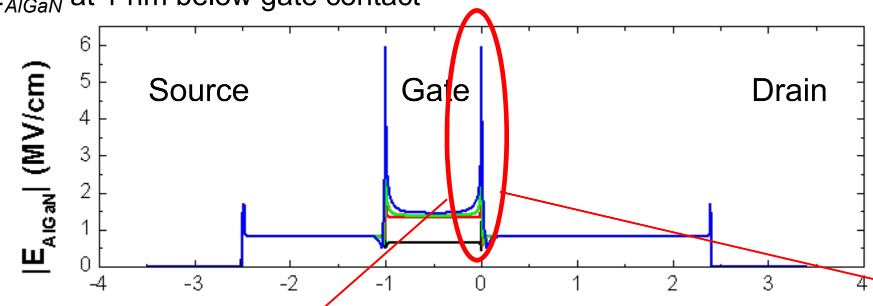
- ψ_S increases with V_G at center of gate → explains E_{AlGaN} saturation
- Large potential drop at gate edges

2D E_{AlGaN} Simulation at Center of Gate

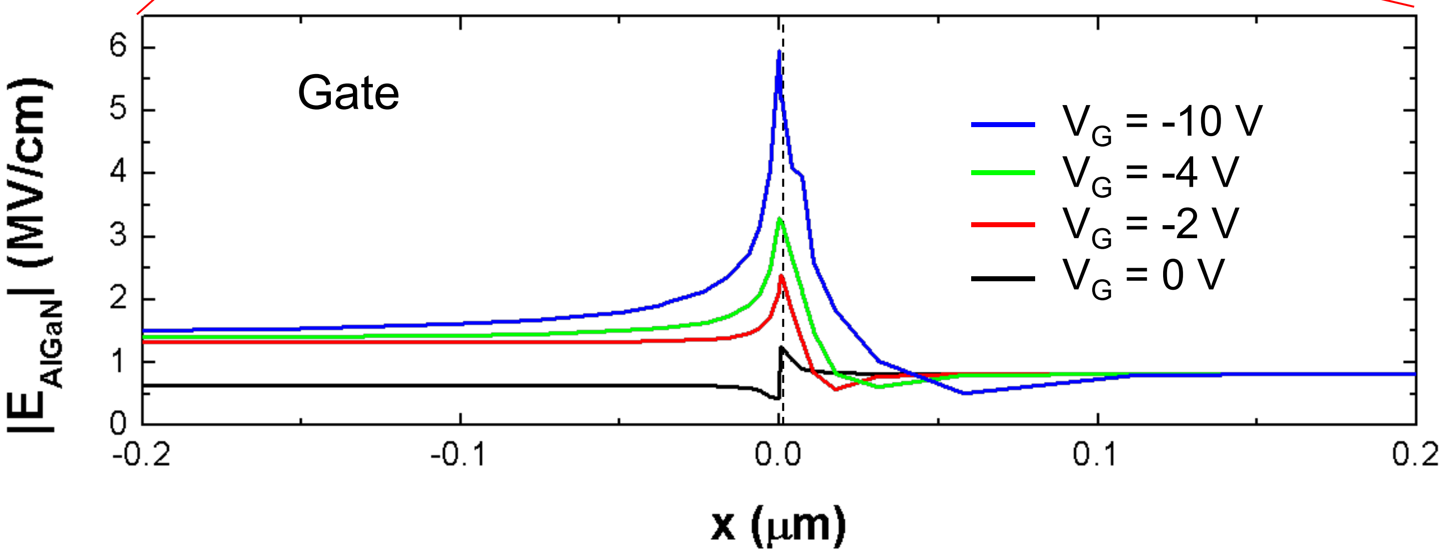


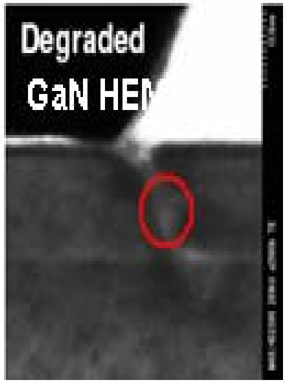
- 2D simulated E_{AlGaN} saturates at center of the gate
- Must analyze the gate edges in more detail

E_{AlGaN} at Gate Edge



- Potential drop at gate edges results in horizontal electric-field increasing $|E_{AlGaN}|$





[J. Joh, et al., IEDM 2007]

E_{AlGaN} peaks at gate edge could cause device breakdown (inverse piezoelectric effect)

Section Summary

- Stress sensitivity of J_G decreases with increasing reverse gate bias
- Explained physics of E_{AlGaN}
  - Saturation under center of gate
  - Peaks at gate edges
- Validated 1D model with experimental data and 2D simulations

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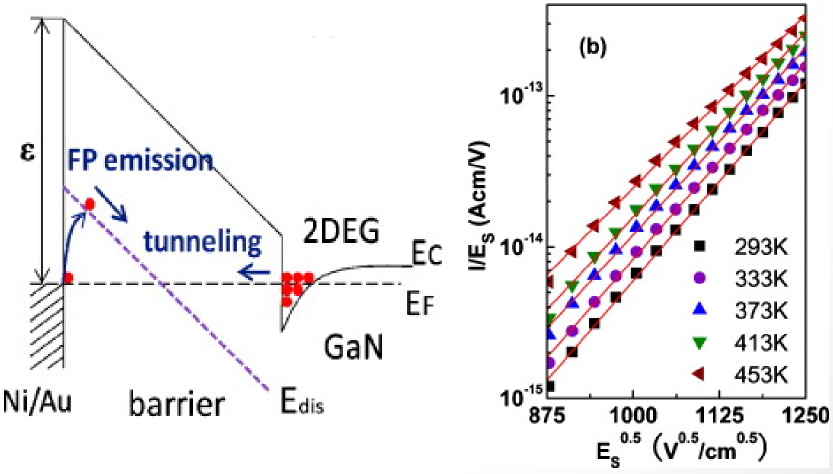
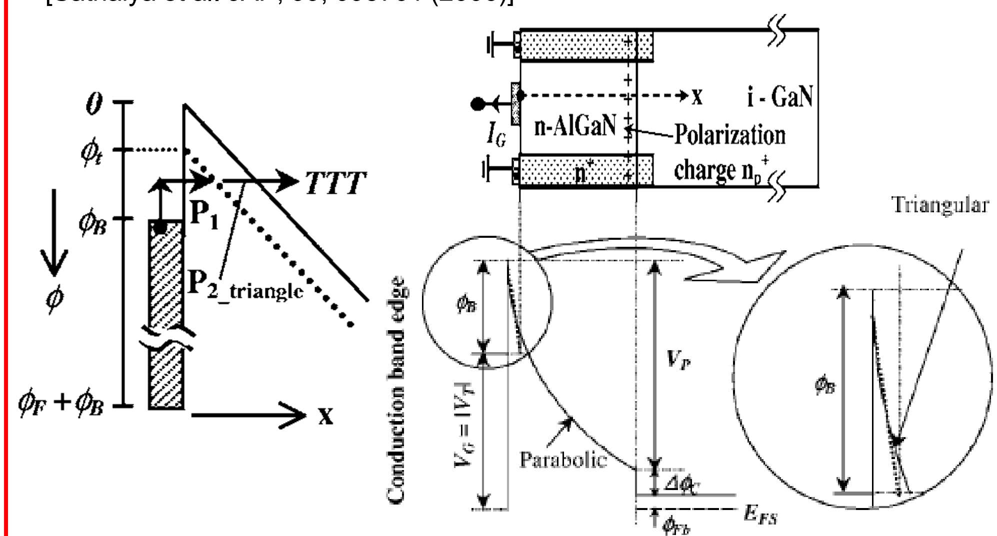
Literature Review on HEMT Gate Leakage

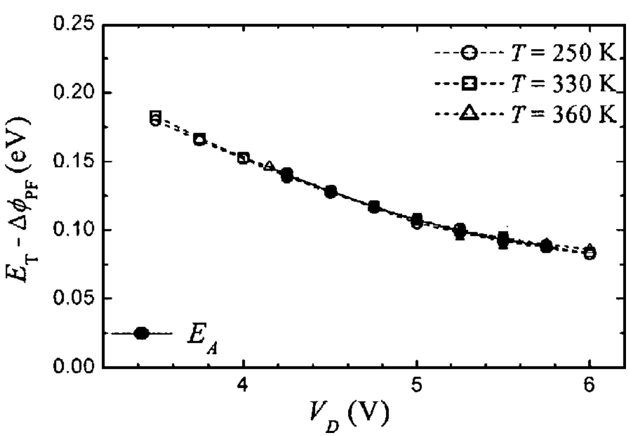
[Yan et al. APL, 97, 153503 (2010)]



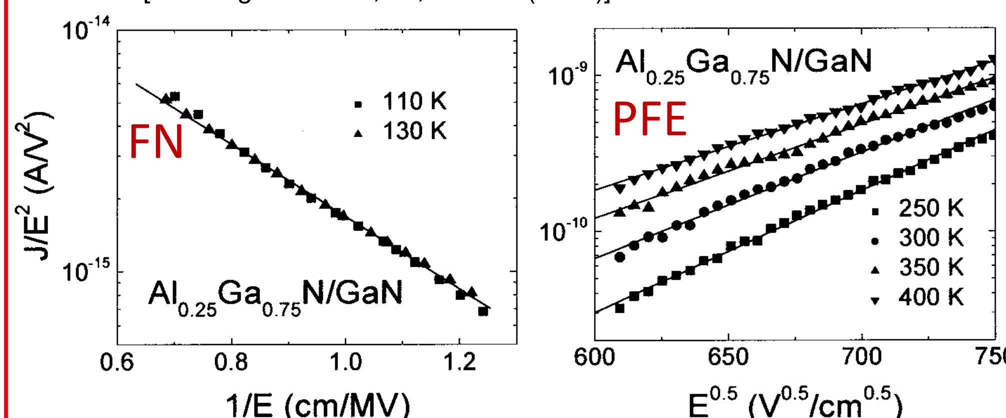
[Sathaiya et al. JAP, 99, 093701 (2006)]



[Mitrofanov et al. JAP, 95, 6414 (2004)]

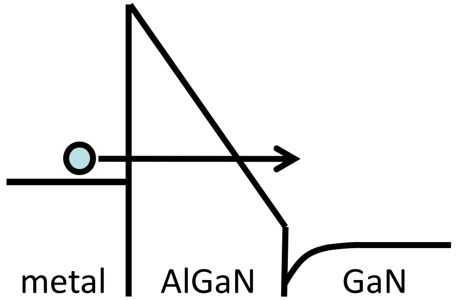


[H Zhang et al. JAP, 99, 023703 (2006)]



Direct Tunneling Formula

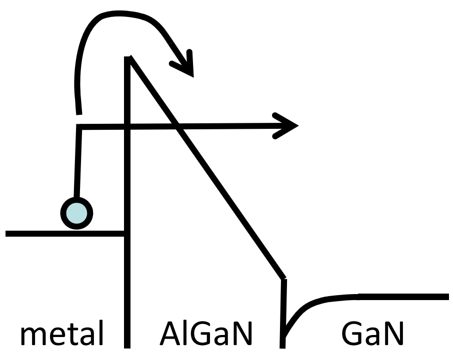
- **Fowler-Nordheim Tunneling**



$$J = \frac{q^2 \left(m_e / m_n^* \right)}{8\pi h \phi_b} E^2 \exp\left(-\frac{8\pi \sqrt{2m_n^* \left(q\phi_b \right)^3}}{3qhE} \right)$$

[Zhang et al. JAP, 99, 023703 (2006)]

- **Thermionic Field Emission**

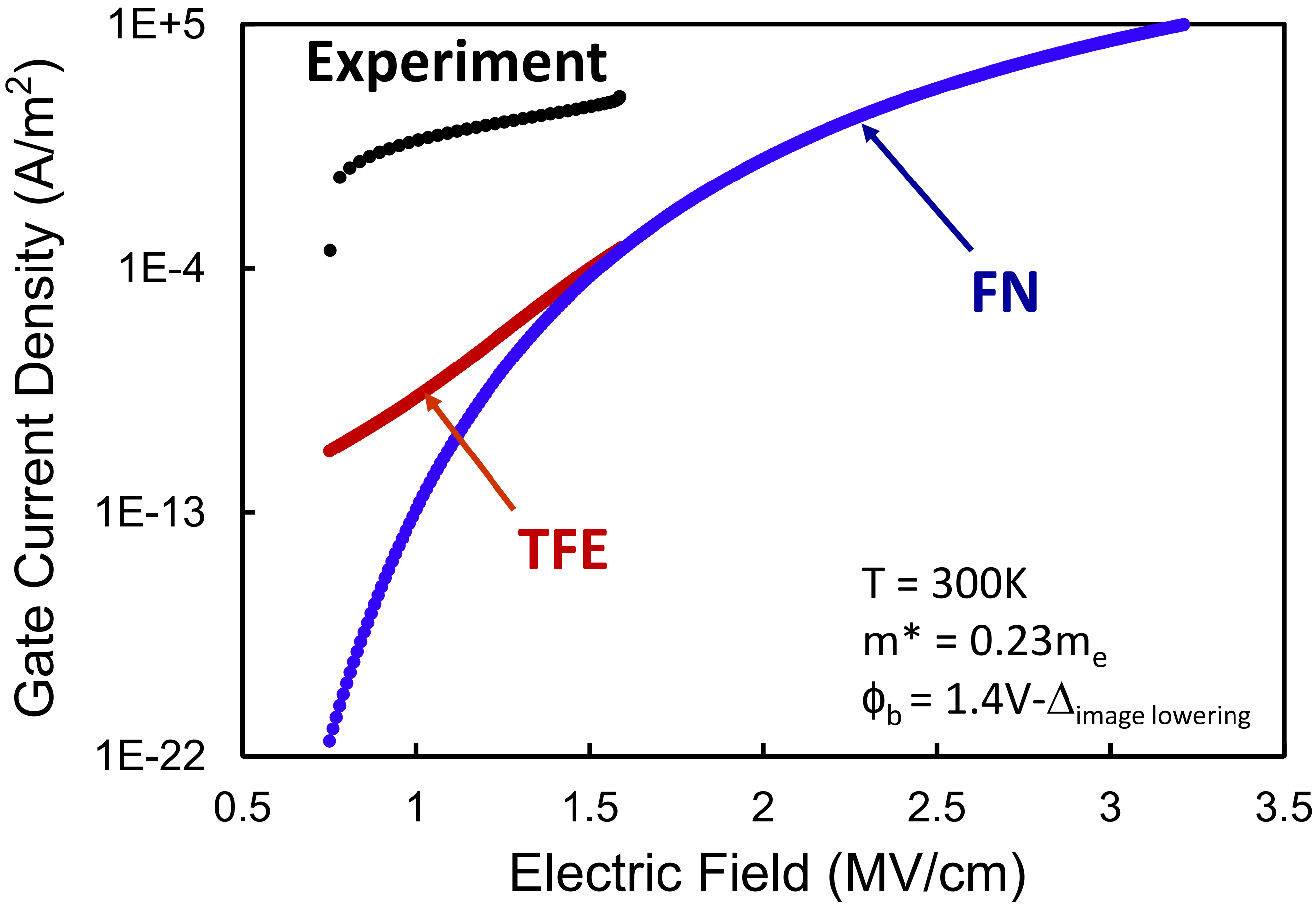


$$J = \frac{qA^* T}{k} \int_0^{\phi_B} f_{FD}(\phi) P(\phi)\, d\phi$$

$$f_{FD} = \frac{1}{1 + \exp\left(\frac{\phi_B - \phi}{kT/q} \right)}, \quad P = \exp\left(-\frac{8\pi \sqrt{2m^* q}}{3hE} \phi^{3/2} \right)$$

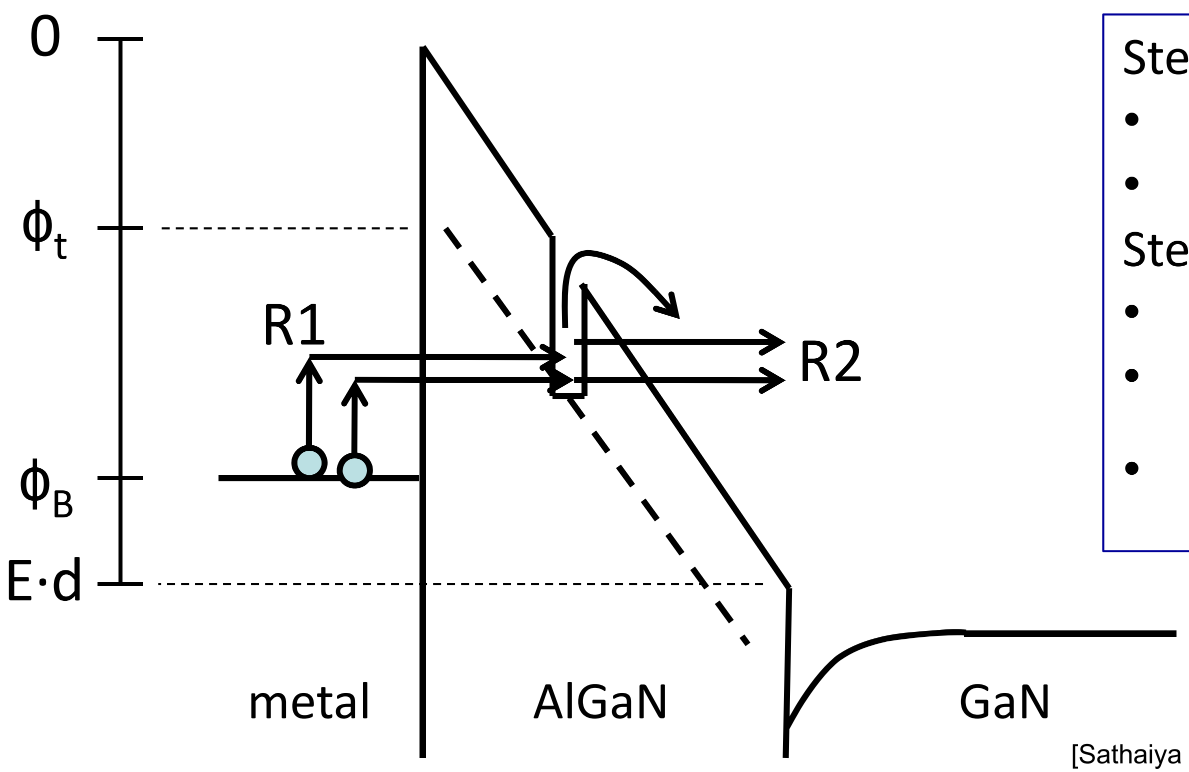
[Karmalkar et al. APL, 82, 3976 (2003)]

Direct Tunneling Current Density



Direct tunneling is unlikely to dominate the reverse gate leakage until at least 2.5MV/cm.

Bulk Trap-Assisted Gate Leakage



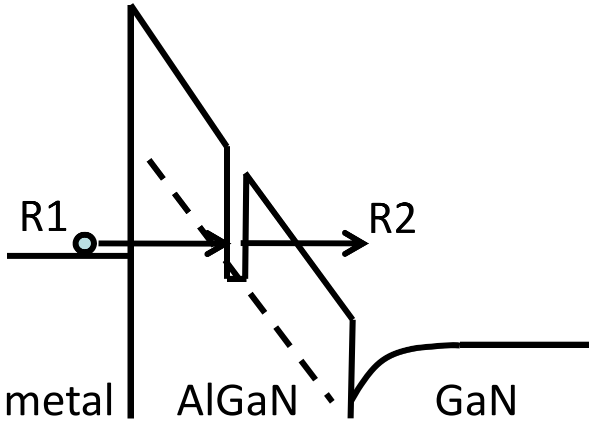
[Sathaiya et al. JAP, 99, 093701 (2006)]

Step 1:
- Direct tunneling
- Thermal assisted tunneling

Step 2:
- Direct tunneling
- Poole-Frenkel emission
  [O Mitrofanov et al. JAP, 95, 6414 (2004)]
- Phonon assisted tunneling
  [P Pipinys et al. JAP, 99, 093709 (2006)]

- Assume uniform trap distribution
- Assume triangular potential within AlGaN
- Only one defect level is considered

Bulk Trap Leakage Model Details



$$R_1 = C_1 N_t f_{FD} \left(1 - f\right) P_1$$

$$R_2 = C_2 N_t f\ P_2$$

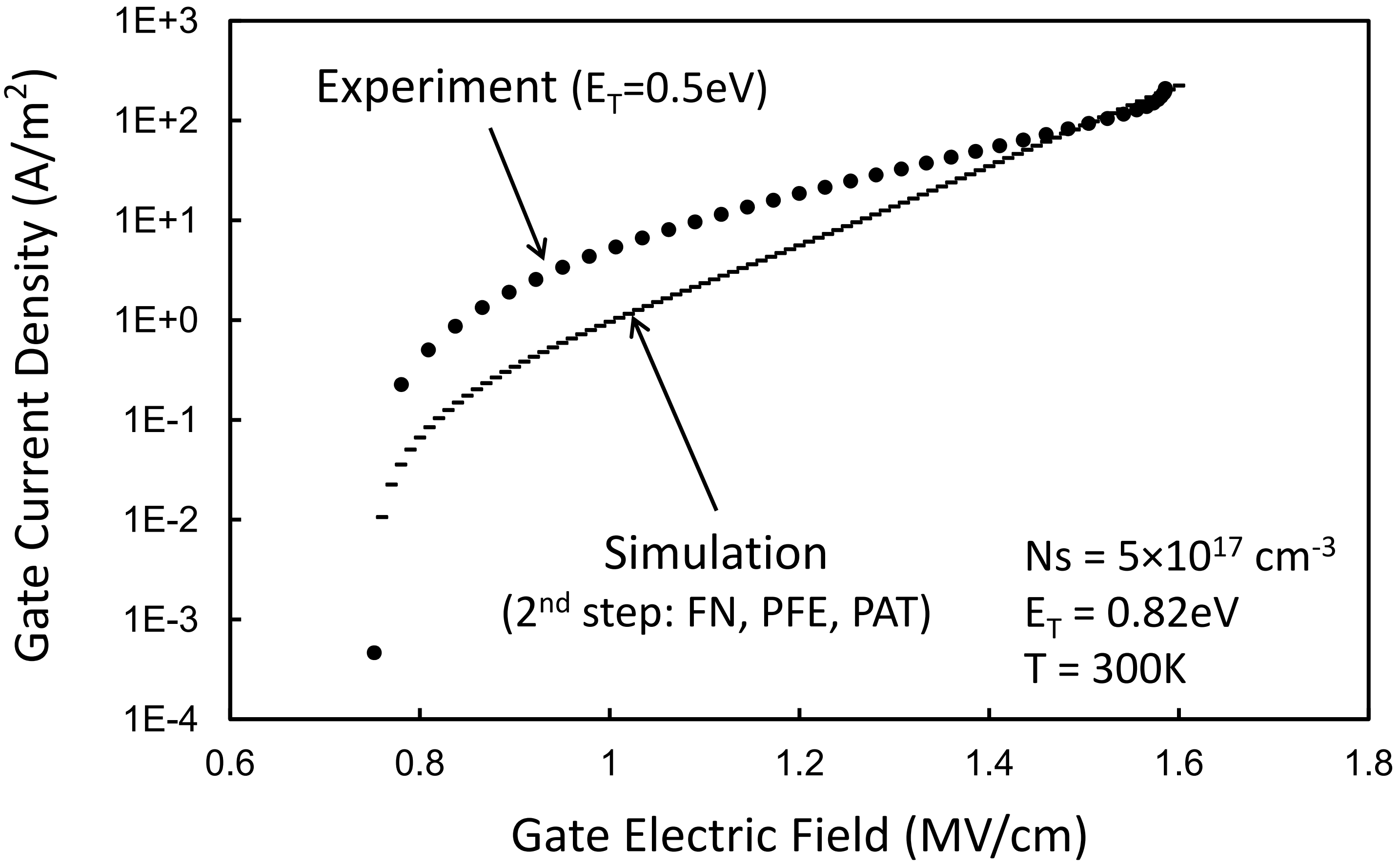
R: tunneling/emission rate
P: tunneling/emission probability
f: probability of a defect state being occupied by an electron

At steady state: $R_1 = R_2 \;\Rightarrow\; C_1 N_t f_{FD} \left(1 - f\right) P_1 = C_2 N_t f\ P_2 \;\Rightarrow\; f = \dfrac{C_1 f_{FD} P_1}{C_1 f_{FD} P_1 + C_2 P_2}$

$$\Rightarrow\; R = \frac{C_1 C_2 N_t f_{FD} P_1 P_2}{C_1 f_{FD} P_1 + C_2 P_2} = N_t \cdot \left(\frac{1}{C_1 f_{FD} P_1} + \frac{1}{C_2 P_2}\right)^{-1}$$

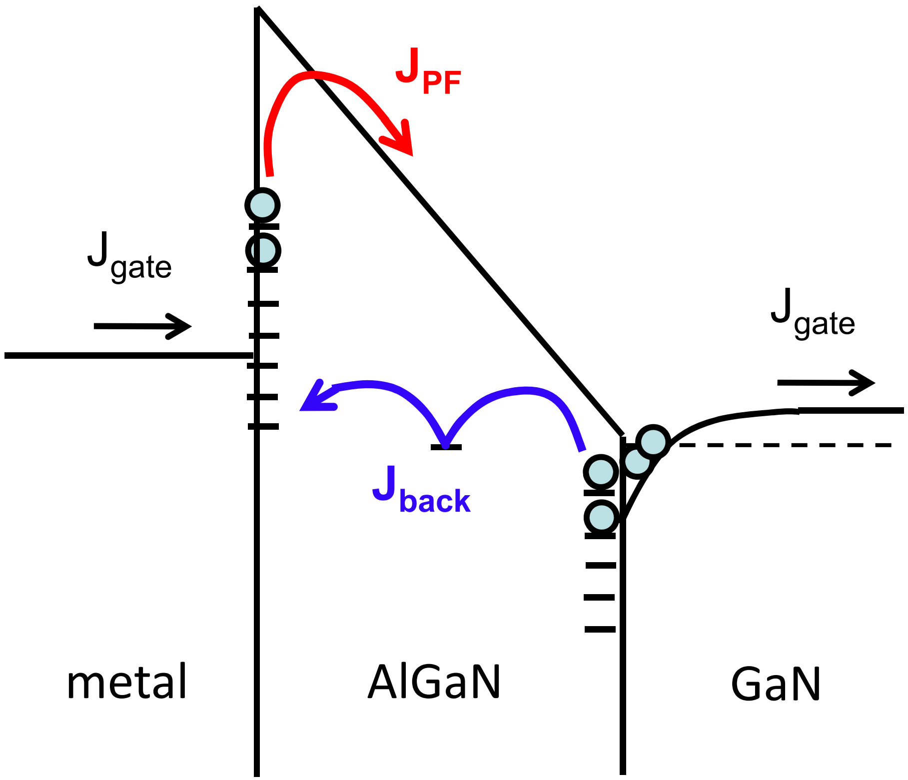
Overall leakage current density: $J = \dfrac{q}{E} \displaystyle\int_{\phi_t}^{E \cdot d} R\left(\phi\right) d\phi$

Gate Leakage Simulation Result



The bulk trap-assisted leakage process is limited by step-1 in which electrons tunnel from metal gate to defect levels.

Poole-Frenkel Emission from Surface States



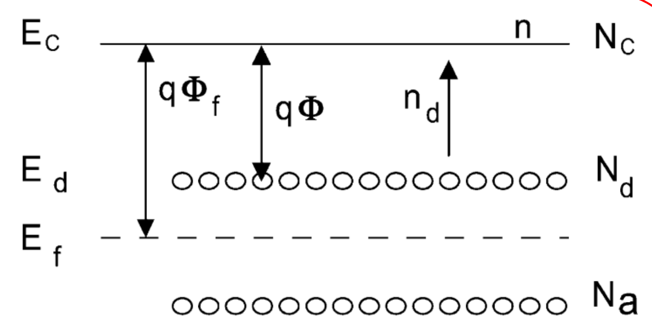
$J_{gate} = J_{PF} - J_{back}$

I_{PF}

$$J_{PF} = CE\exp\left(-\frac{E_T - \Delta\phi_T}{rkT}\right),$$

$$\text{where} \quad \Delta\phi_T = \beta\sqrt{E} = \sqrt{\frac{q^3 E}{\pi\varepsilon_{AlGaN}}}$$

[Yeargan et al. JAP, 39, 5600 (1968)]



[Harrell, et al. Thin Solid Films, 2002]

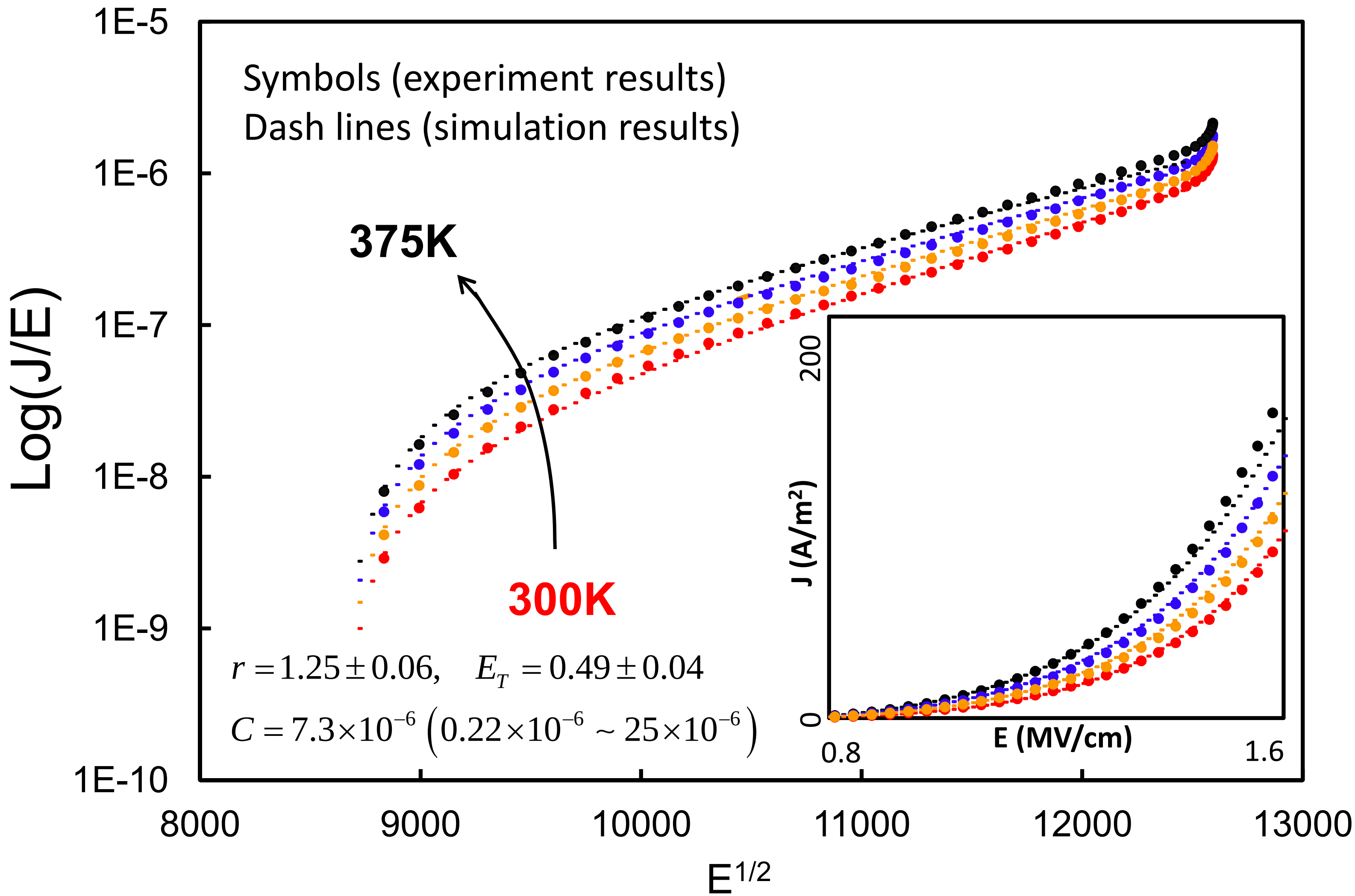
I_{back}

$$J_{back} = C'\exp\left(-\frac{\alpha\sqrt{m^*}}{E}\right)$$

[Yan et al. APL, 97, 153503 (2010)]

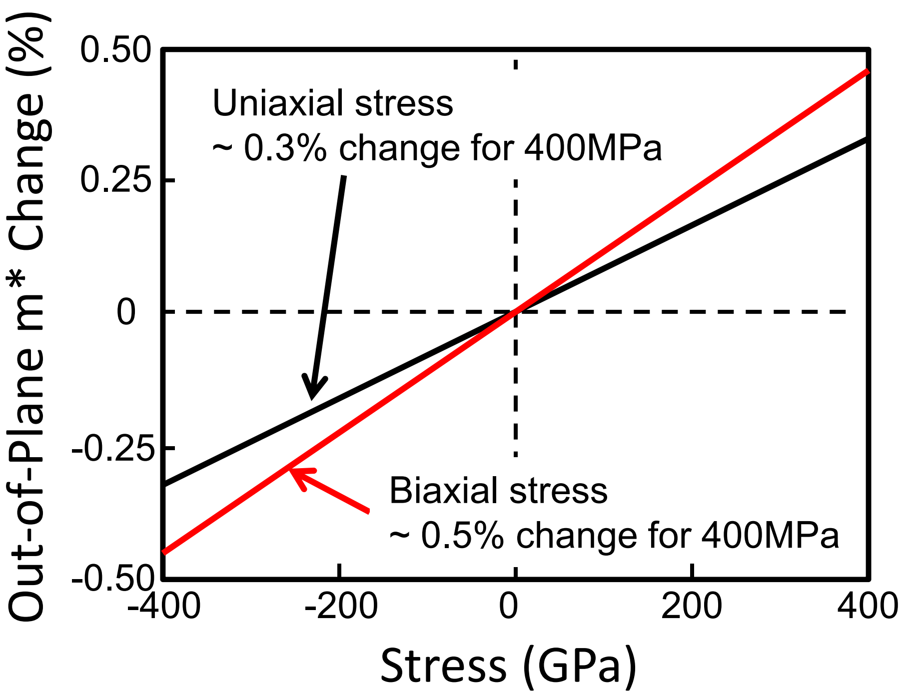
I_{PF} increases dramatically and I_{back} is negligible once V_g<0.

Poole-Frenkel Emission from Surface States

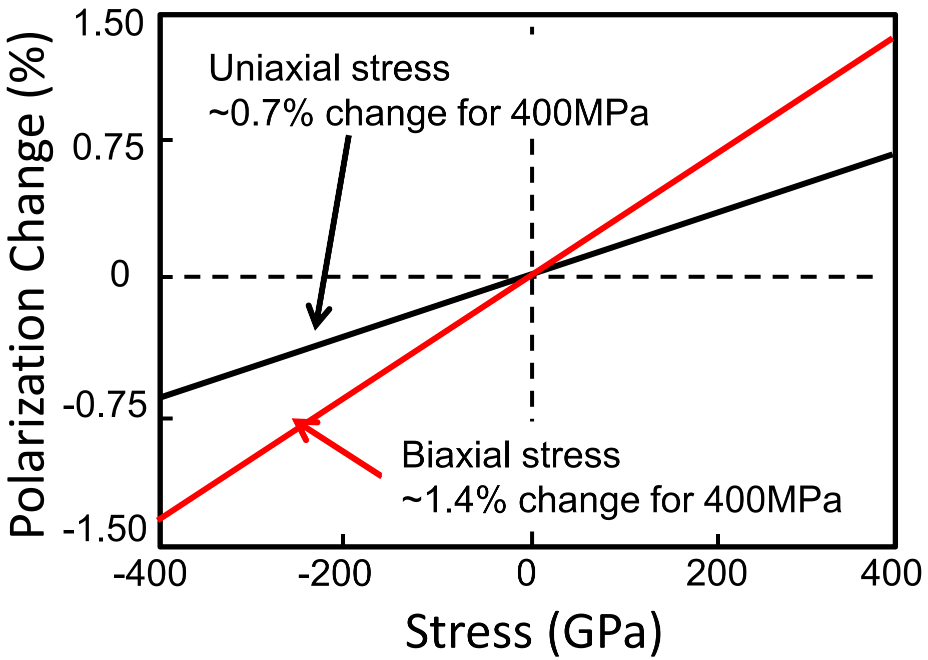


Stress-Altered Effective Mass and Field

Effective mass change

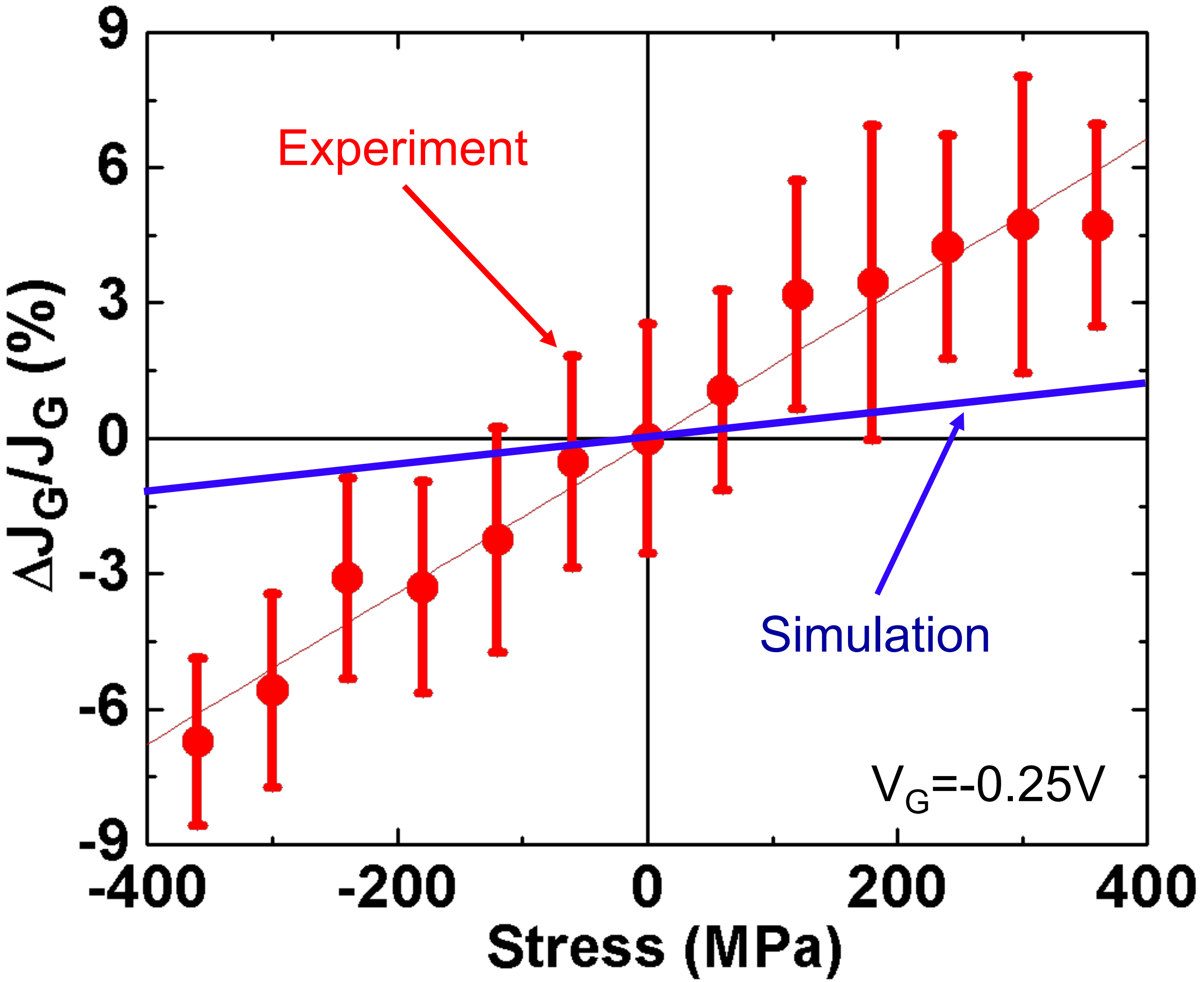


Electric field change

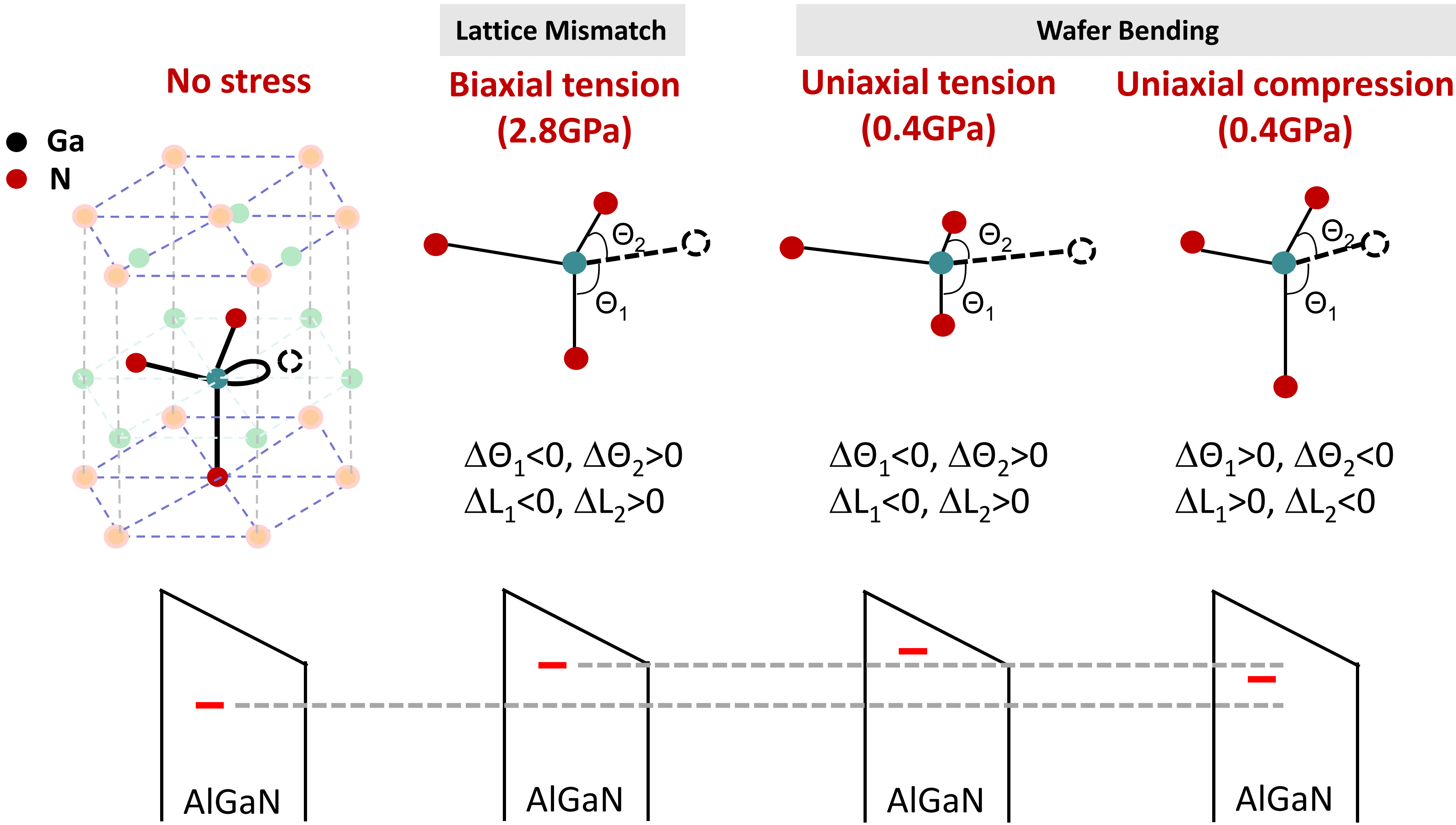


- sp^3d^5 tight-binding model was used to simulate m_{out}
- $\Delta E_{field} = \Delta P_{piezoelectric}$

Stress-Altered J_G Based on Δm^* and ΔE

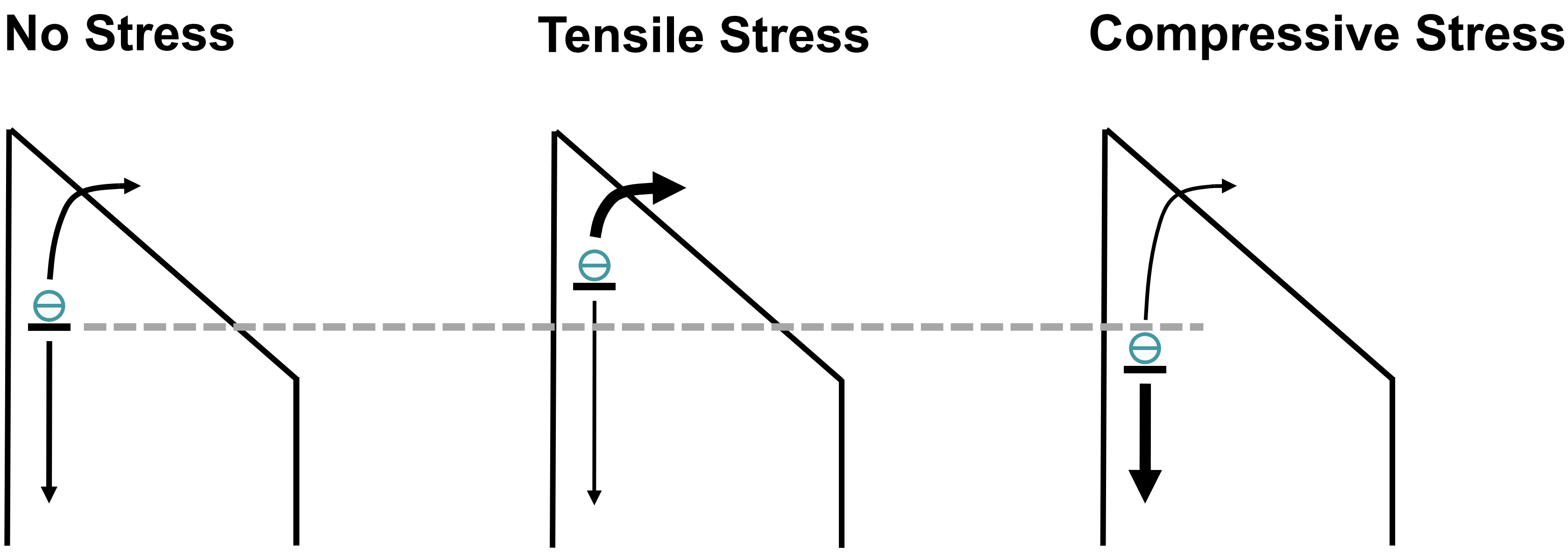


Stress-Altered E_T – Qualitative Argument



[Choi et al. APL vol. 92, pp. 173507 (2004)]

Stress-Altered *r*-Parameter



$r_{original}$

Less compensation
$\Delta r > 0$

Heavy compensation
$\Delta r < 0$

- ΔE_T and Δr are treated as fitting parameters

Stress affects gate leakage current mainly through ΔE_T and Δr.

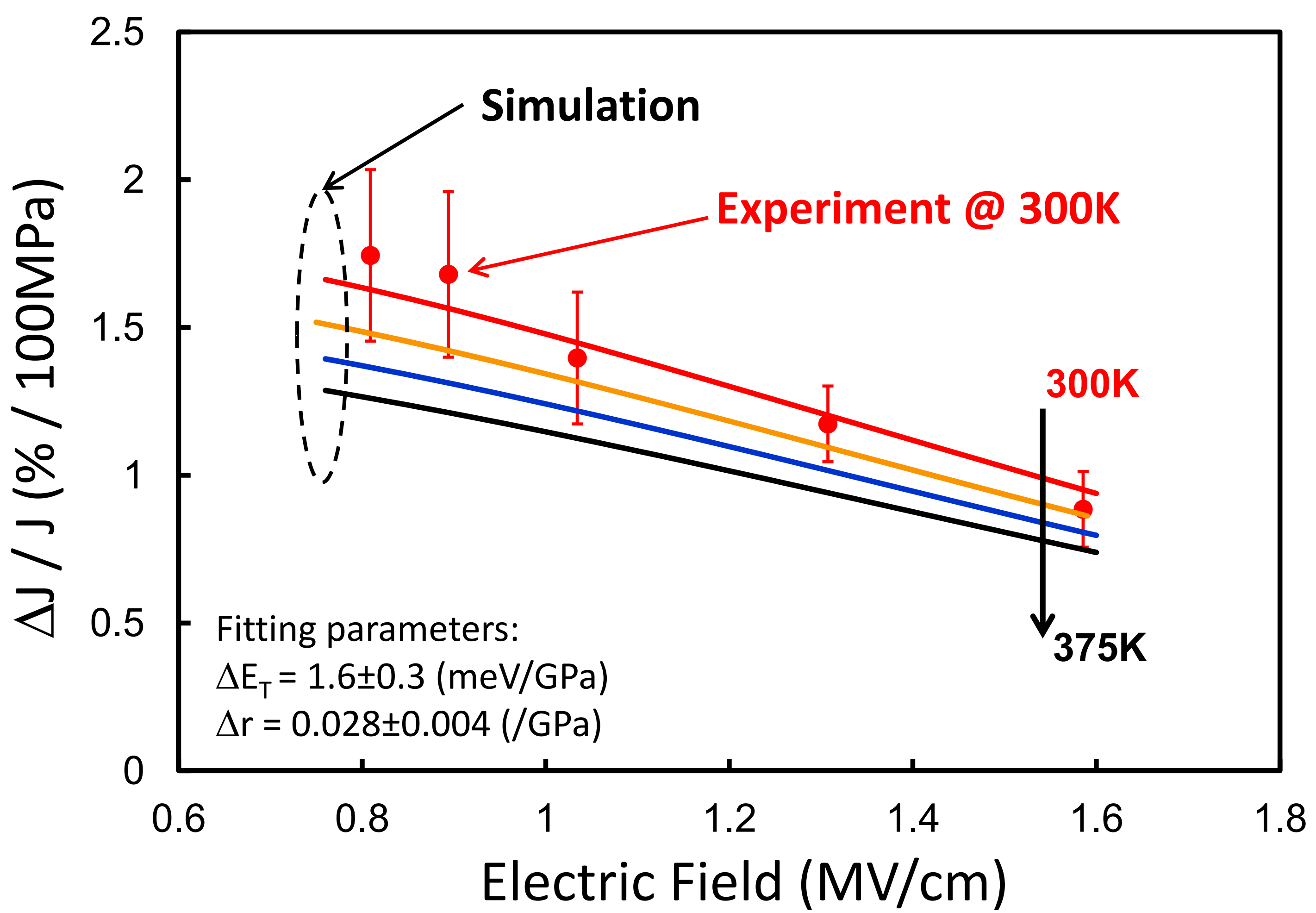
Stress-Altered Gate Leakage Calculation

$$J_{\sigma=0} = CE\exp\left(-\frac{E_T - \Delta\phi_T}{rkT}\right) - C'\exp\left(-\frac{\alpha\sqrt{m^*}}{E}\right)$$

$$J_{\sigma\neq0} = C\left(E+\Delta E\right)\exp\left(-\frac{\left(E_T+\Delta E_T\right)-\Delta\phi_T}{\left(r+\Delta r\right)kT}\right) - C'\exp\left(-\frac{\alpha\sqrt{\left(m^*+\Delta m^*\right)}}{\left(E+\Delta E\right)}\right)$$

$$\frac{\Delta J_G}{J_G} = \frac{J_{\sigma\neq0} - J_{\sigma=0}}{J_{\sigma=0}}$$

Effect of Stress on J_G



I_{gate} increases/decreases under uniaxial tension/compression.

Section Summary

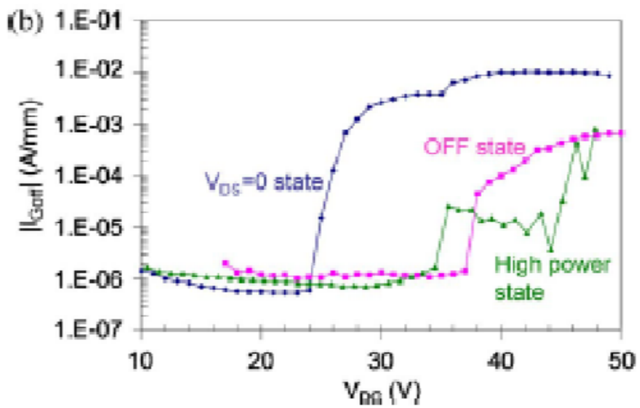
- Investigated the possible gate current mechanism of the reverse-biased GaN HEMT
- Determined the PFE from surface state to be the dominant leakage mechanism
- Simulated and understood the stress dependence of J_{gate}.
- Collaborate with Erin Patrick for FLOODS gate leakage modeling

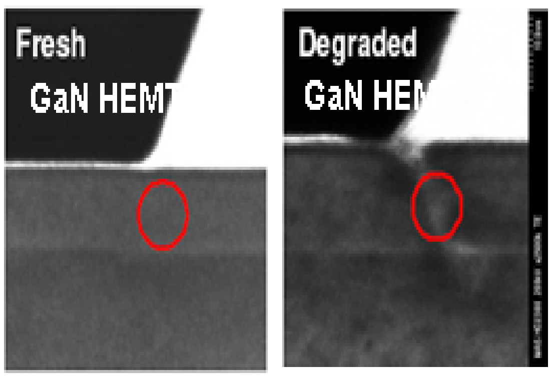
Outline

- Motivation
- Stress Dependence of Gate Current and Characterization of Electric Field in AlGaN Barrier
- Simulation of the Dominant Stress-Altered Gate Leakage Current
- **Gate Current Degradation under Mechanical and Electrical Stress**
- Summary

AlGaN/GaN HEMT Degradation

Theory I :

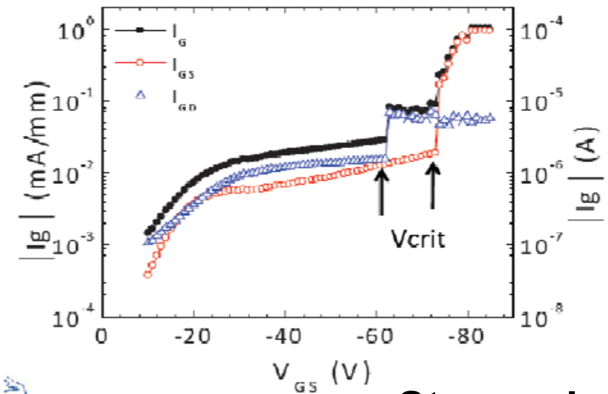




• Crystallographic defect-formation due to inverse piezoelectric effect

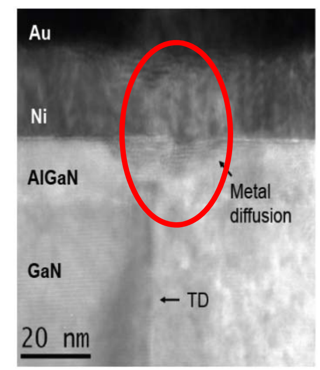
[Dr. del Alamo's group]

Theory II :



Fresh Device

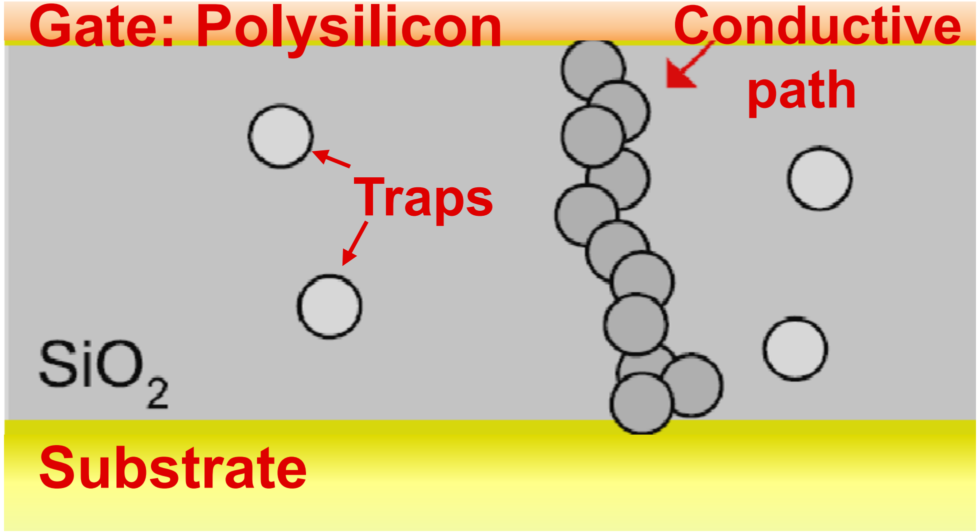
Stressed Device

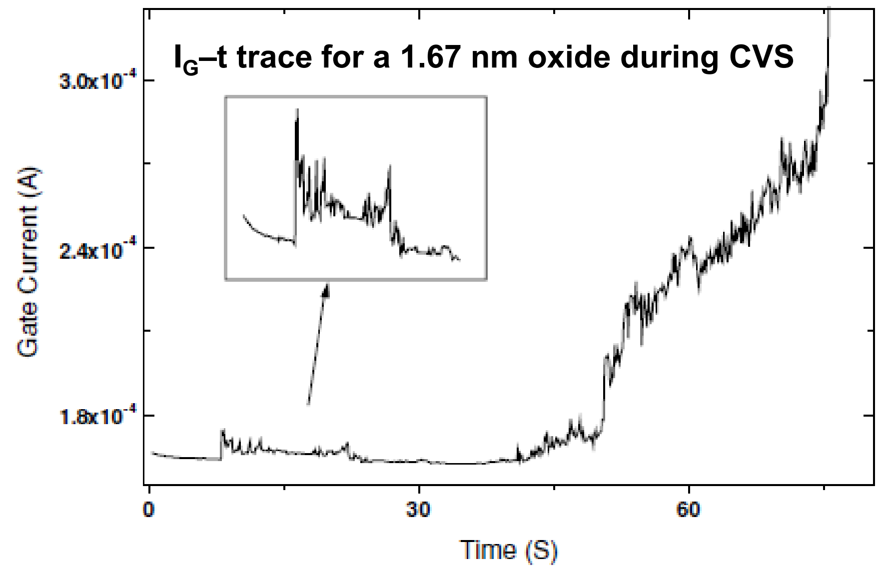


• Metal diffusion from gate into AlGaN layer

[Dr. Fan Ren's group]

Si MOS Gate Oxide Breakdown

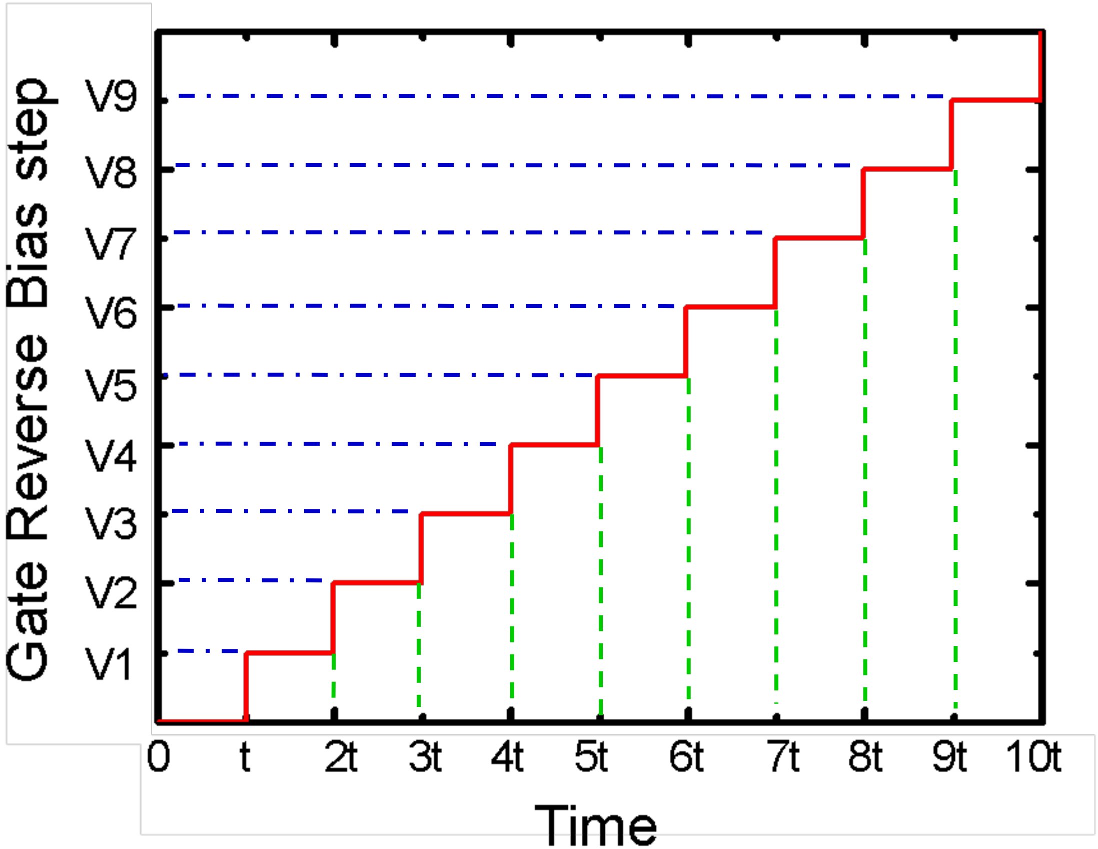




[*Robert O' Connor et. al. Semicond. Sci. Technol. 2005*]

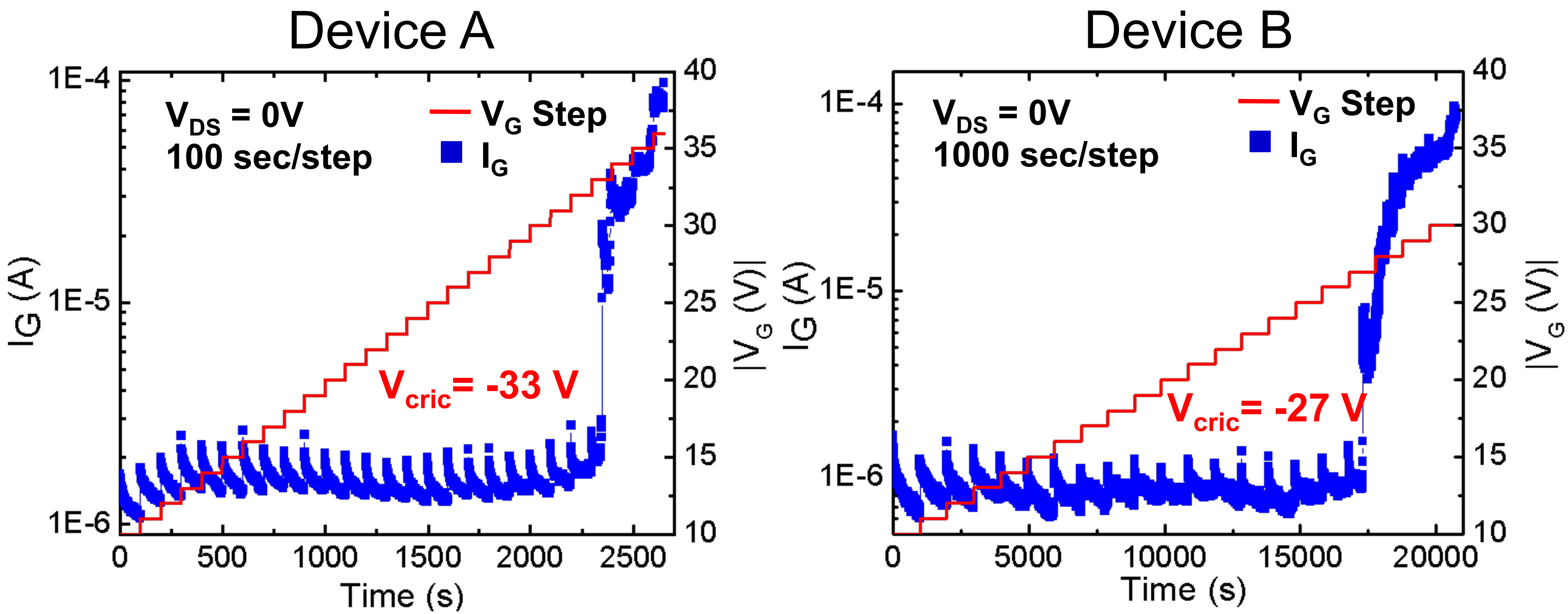
- Oxide breakdown is marked by sudden increase of leakage current.
- Breakdown occurs due to clustering of trapped charges at localized sites, leading to enhanced conduction.
- Breakdown can be Soft Breakdown (SBD) or Hard Breakdown (HBD).

Time Dependent Electrical Step Stressing



- Vary length ‘t’ of each E-stress step.
- Perform step stress test on GaN HEMTs, with t=10sec, 100sec, 500sec, 1000sec, and measure I_G simultaneously.

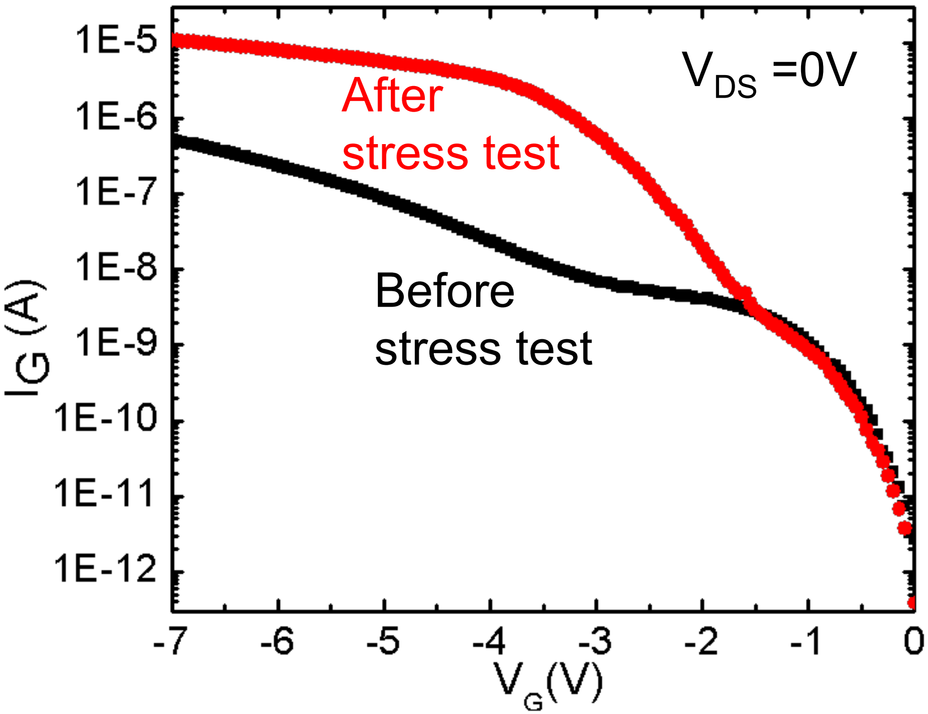
Time Dependent Electrical Step Stressing Results



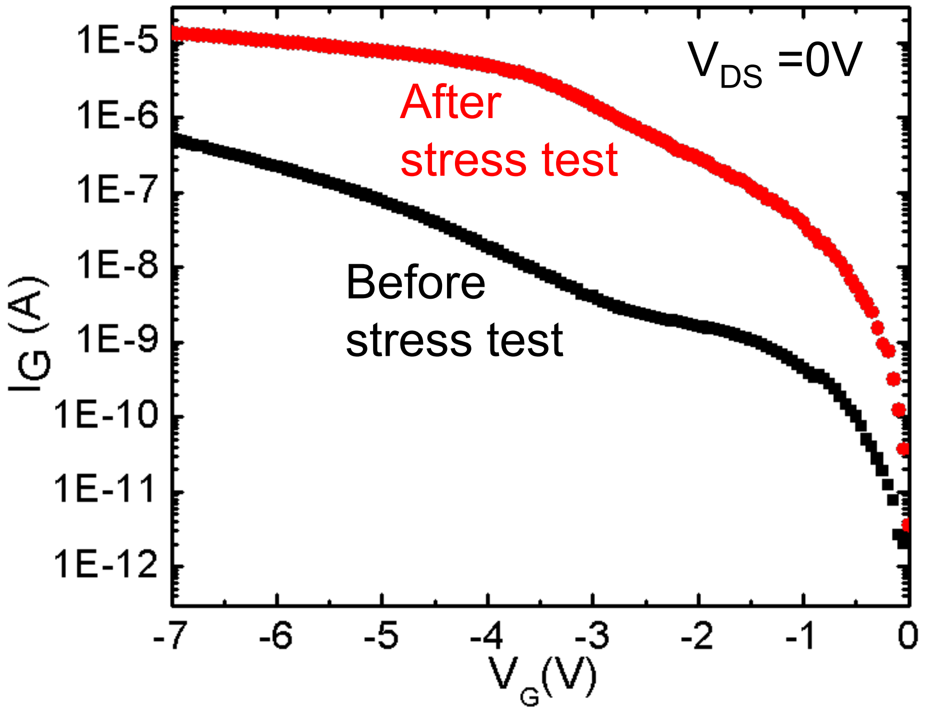
- Trapping transients are observed at each stress step prior to breakdown.
- One large sudden increase in I_G is observed, followed by multiple small jumps in I_G

I_G-V_G after Electrical Step Stressing

Device A

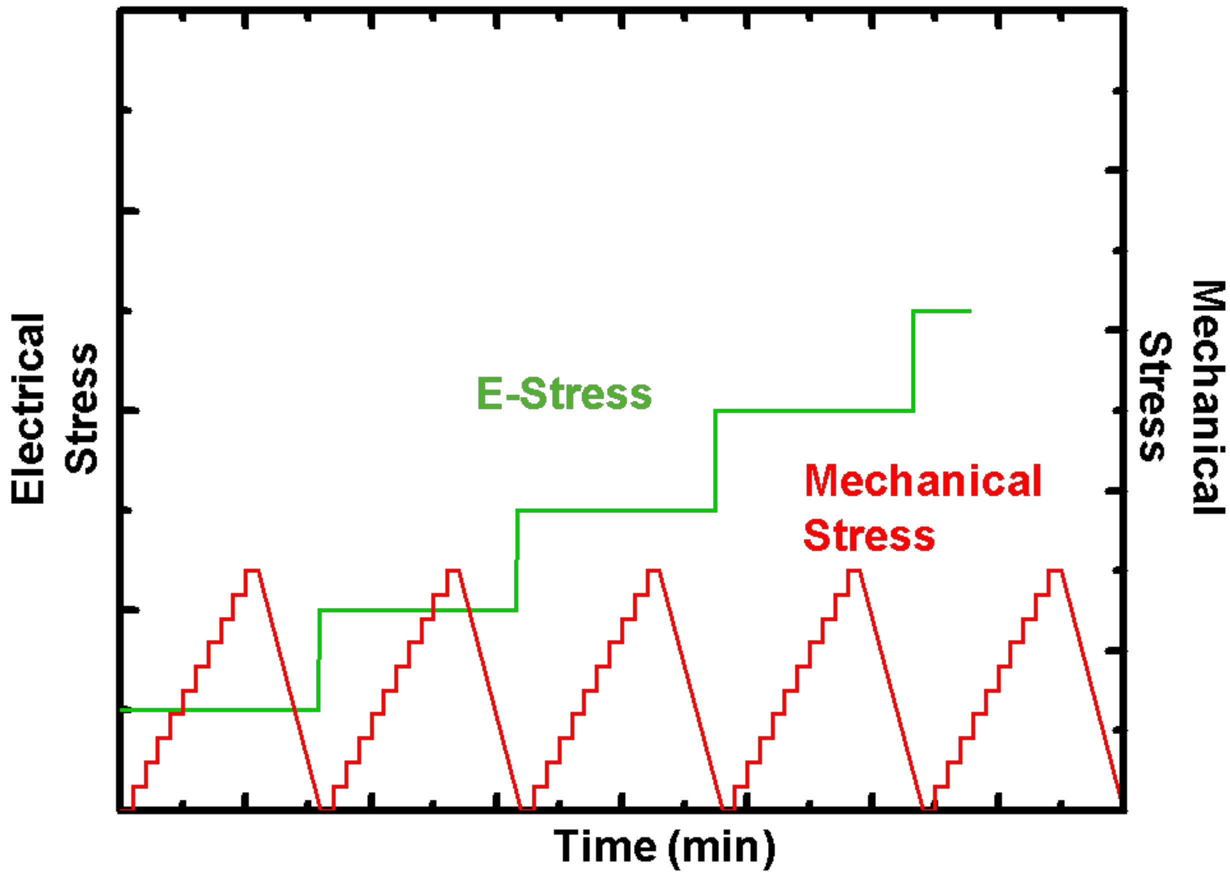


Device B



- Increase in I_G is observed after device degradation

Combined Electrical and Mechanical Stressing



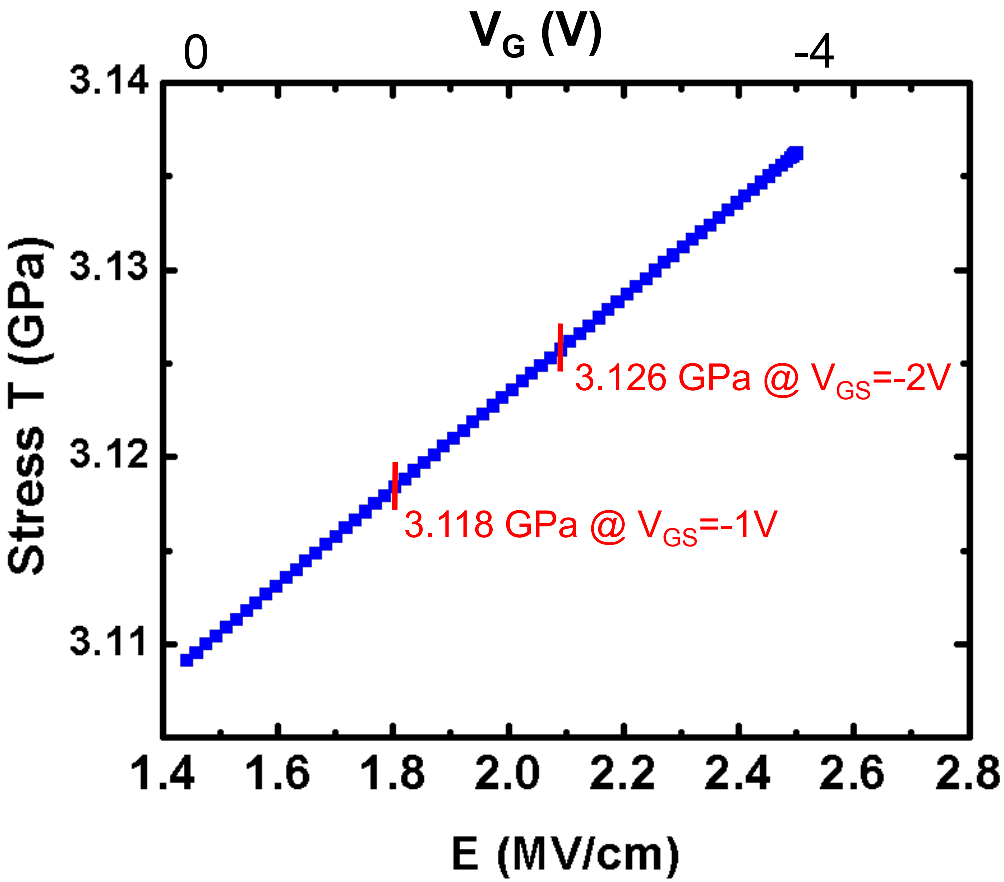
- Measure I_G during the application of stress
- Need to determine step size for E-stress and mechanical stress

Piezoelectric Constitutive Relation

$$T = c_E . S - e^t . E$$

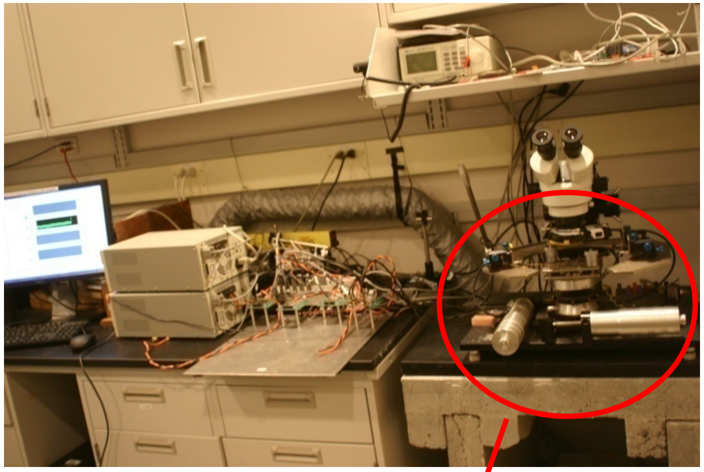
$$S = s_E . T + d^t . E$$

T= Stress matrix (6X1)
S = Strain matrix (6X1)
E = Field (3X1)
c_E= stiffness matrix (6X6)
s_E= compliance matrix (6X6)
d^t,e^t= piezoelectric matrix (3X6)

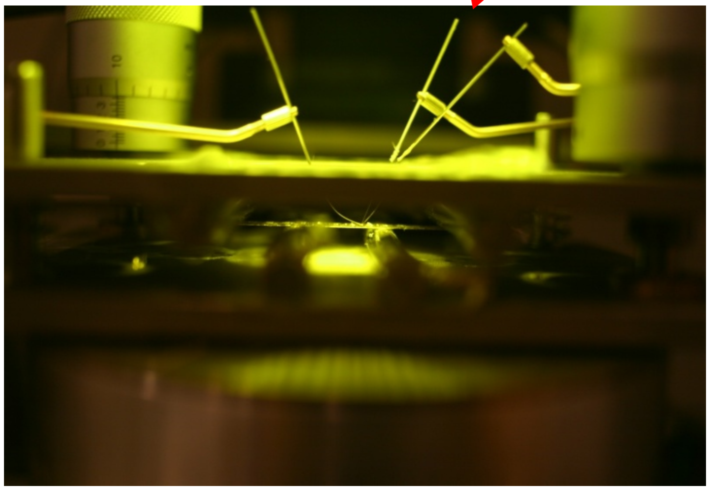


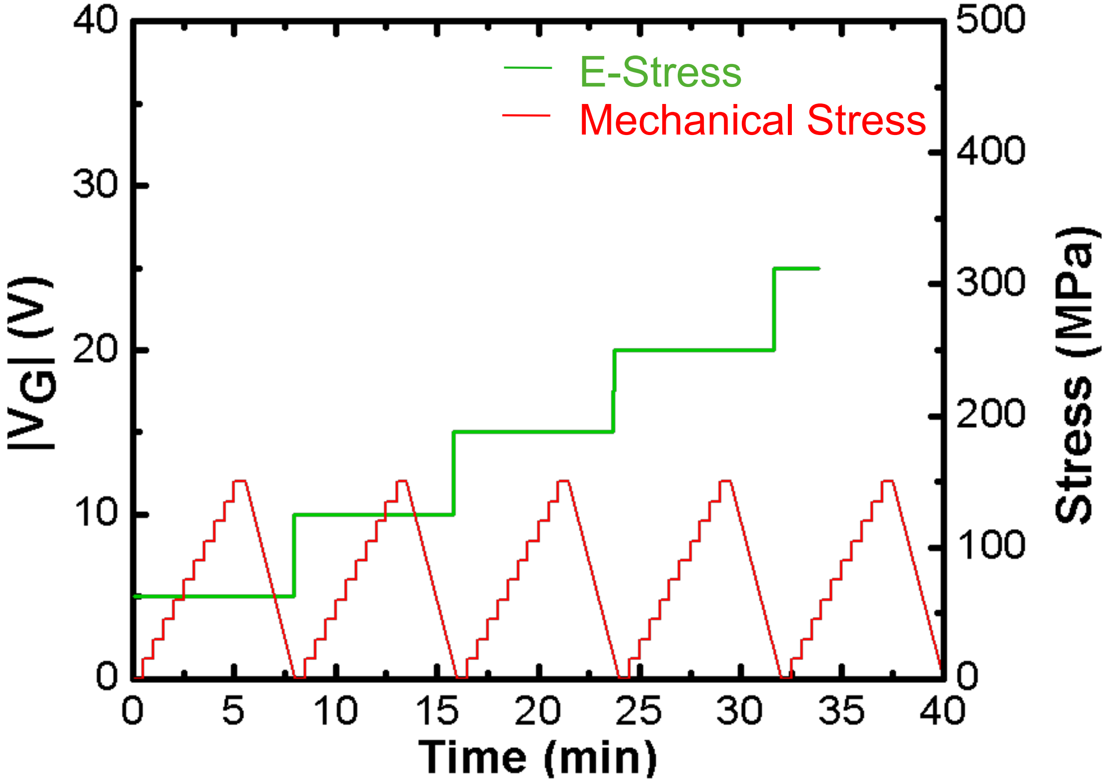
- -1V of V_G generates ~10 MPa of biaxial tensile stress

Experimental Set Up



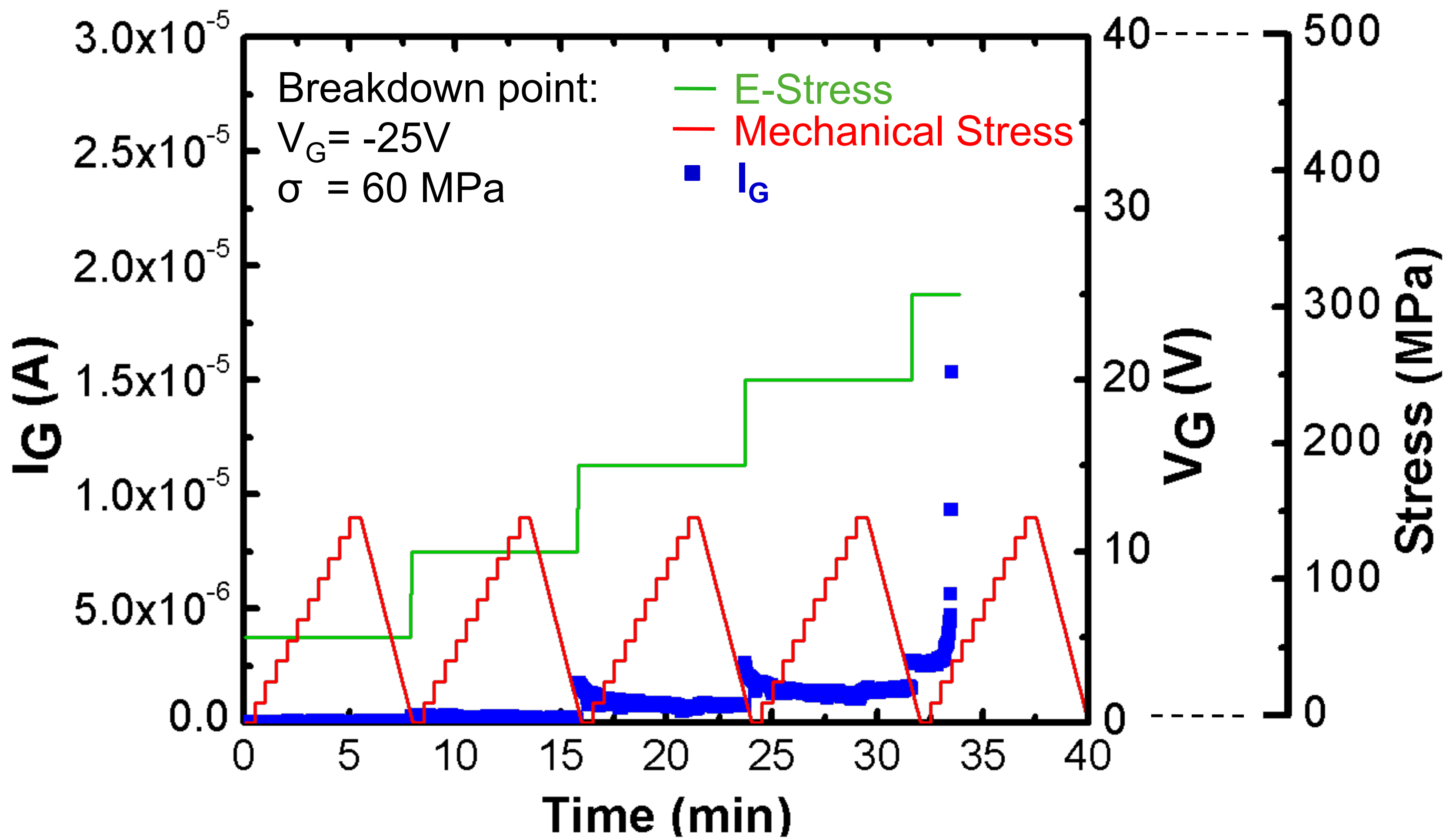
Courtesy, David Cheney





- V_G step size is -5V, each applied for 8min
- Uniaxial mechanical stress is applied in steps of 15 MPa, upto 150 MPa max.

I_G Degradation under Electrical-Mechanical stress



Section Summary

- Measured I_G under E stress stepping at varying lengths of stress step
- Device Flow: AFRL ↔ E-stress ↔ Mechanical Stress for t>0
  - Integrated mechanical stress and electrical stress to perform degradation experiments

Summary and Future Work

- Investigated the dominant leakage mechanism to be PFE in reverse-biased AlGaN/GaN HEMT
  - Stress sensitivity of gate current decreases with increasing reverse bias
- Determined that inverse piezoelectric effect plays significant role in AlGaN/GaN HEMT failure
- Device Flow: AFRL ↔ E Stress ↔ Mechanical Stress
  - (next to LEAP)
- Theory Flow: Stress dependent gate leakage modeling ↔ Electromechanical (FLOORS)

Acknowledgments

MURI FUNDING

Effect of Mechanical Stress on Gate Current and Degradation in AlGaN/GaN HEMTs

QUESTIONS?